

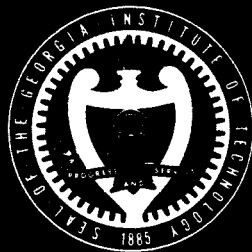
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MECHANICAL DESIGN ENGINEERING
NASA/UNIVERSITY
ADVANCED MISSIONS SPACE DESIGN PROGRAM

LUNAR ARTHROPOD CONFIGURATION
WALKING CHASSIS

March 1987

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Lunar Arthropod
Mobile Platform
- 'Skitter'

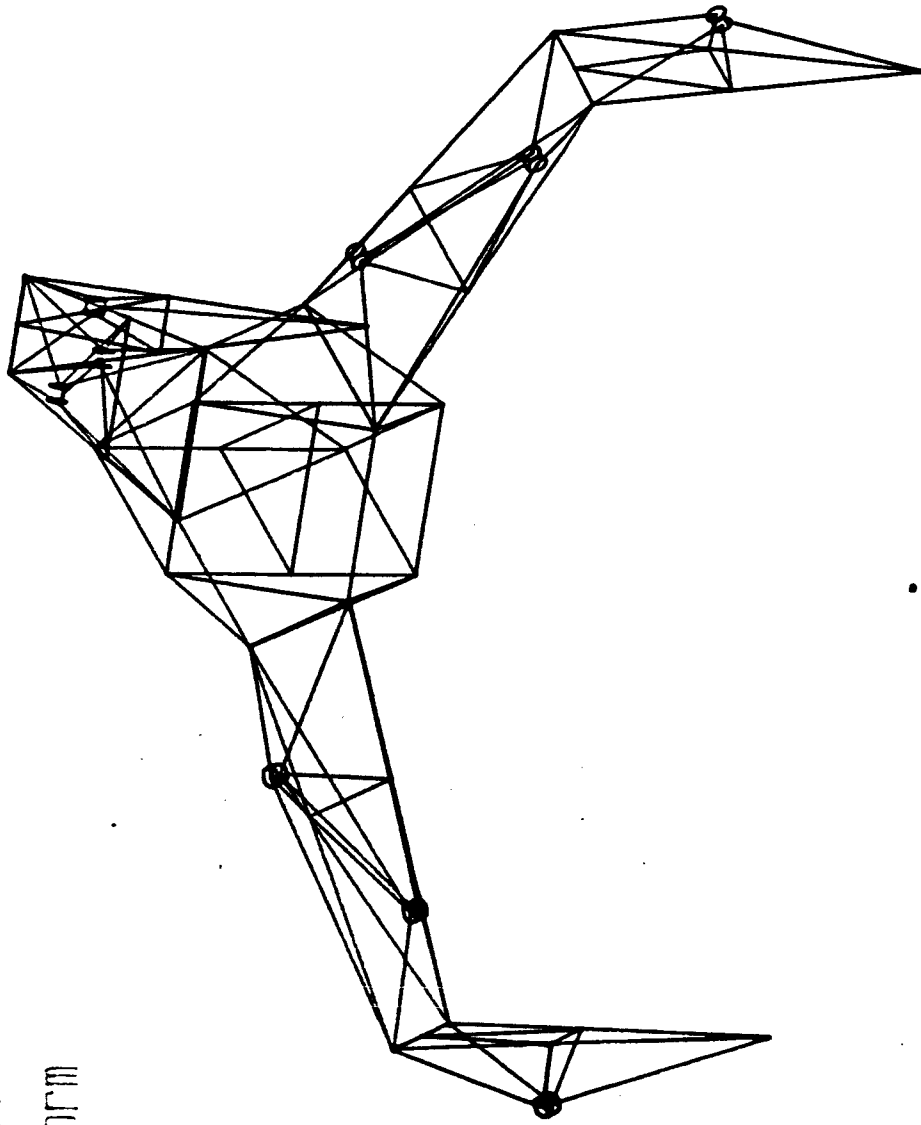


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ABSTRACT

The purpose of this project was to design a new leg for the skitter. The skitter requires much dexterity because of the broad nature of its duties. It will serve as the base for a number of implements used for construction on the moon. As of now, these implements are a crane, a drill, a soil bagger, and a digger. A femur-tibia configuration was chosen because this will provide the skitter with much more dexterity with a minimum amount of added complexity.

Each part of the leg is of a space truss design. The individual members are constructed of a boron/epoxy composite for weight savings while maintaining high strength. The members are connected by titanium joint fittings.

Pin joints lubricated by Teflon™ are used at the leg joints. There is one moving joint between the femur and the skitter body and another between the femur and the tibia. A solid lubricant was chosen for trouble free operation. Appropriate devices are used to protect the solid lubricant bearings from the lunar environment.

Relative motion will be provided by ball screw actuators. These were chosen because they are the present actuator of choice for space applications. The actuators will be driven by AC motors and will have brakes since they are not self-locking.

A somewhat spherical foot is used at the end of the leg to provide for good traction at all leg angles with respect to the

ground. The foot has been designed with no moving parts to increase its reliability.

PROBLEM STATEMENT

BACKGROUND

The purpose of this project is to alter the existing leg design of a three-legged mobile platform intended to operate on the lunar surface. The intent in doing this is to add dexterity to the support system while adding a minimum amount of complexity to the design. The design will incorporate a multi-jointed leg of the femur-tibia configuration. This project will seek to optimize this configuration by taking into account all pertinent parameters including but not limited to material, stresses, structure, and mobility.

PERFORMANCE

1. The leg should have a four meter vertical stroke somewhere along its travel.
2. The leg should withstand all loads from any implements that are planned to be attached to the skitter.
3. The leg should allow the skitter to walk up and down and traverse specified slopes.
4. The leg should be designed for minimum weight thus reducing its transportation cost and energy requirement during operation.

5. The leg should be designed for maximum possible strength.
6. The leg should be built at minimum life-cycle cost.
7. The leg should be of minimum complexity / maximum reliability.
8. The leg should place the center of gravity of the skitter as low as possible during normal operations.
9. The actuators used should have a fast enough stroke to perform their required task.

CONSTRAINTS

1. The leg should be able to operate in the lunar environment; specifically, it should withstand a hard vacuum and temperatures ranging from -200F to 200F.
2. The skitter must fit in the shuttle cargo bay area.
3. The resonant frequency of the leg must be suitable for transporting on the shuttle.
4. It is desired that the skitter have a 6m max clearance.

DESCRIPTION

The skitter will be a multi-use platform which, as of now, is intended mainly for construction work on the lunar surface. It will have several implements that can be attached to it through an interface, which will transfer loads from the implement to the skitter's frame. As of now, the implements being designed for attachment to the skitter are a digger, a drill, a crane, and a soil bagger. Because of the multifarious capabilities of these implements, the skitter's design has many jobs to perform.

For instance, for the digger it is necessary that the legs of the skitter can be moved as far as possible from the digging area. This is done to provide the digger with a maximal work envelope so that little time is spent maneuvering around the legs. Also, it is desired that the skitter be as high as possible for the same reason of providing a large work envelope.

For the drill, the main requirement was that a four meter vertical stroke could be obtained solely by movement of the skitter. This was required so that the drill would not require any hardware to provide for vertical movement. Also, the skitter must be able to absorb the torques produced from drilling.

For the crane, the skitter will serve as an outrigger. The legs will be splayed out to approximately seventy percent of their full reach. This is the most demanding job of the skitter as it is desired that 4000 moon pounds be the capacity of the

crane. However, it was found that to accommodate this load the legs and actuators of the skitter have to be grossly overdesigned with respect to the requirements of the other implements (see Conclusions and Recommendations, and Appendix 1a).

The soil bagger levies the smallest requirements from the skitter. The soil bagger needs horizontal movement in order to scrape the ground to obtain soil. The skitter is not able to provide much horizontal movement by swaying, it would have to pick its legs up and replant them. Since this was not acceptable for the soil bagging implement, they designed the horizontal movement into their implement. Therefore, the skitter serves the soil bagging implement only as a mode of transportation.

In order to better satisfy the above requirements, the previous leg design needed to be changed. The old leg had one member and two actuators. One actuator provided for angular displacement relative to the skitter frame and the other actuator, situated at the end of the leg, served as a leg extender. The new leg design has two members, a femur and a tibia, and two actuators per leg. This allows for a larger operating envelope of the leg.

The upper leg member, the femur, is of a space truss design comprised of 23 separate members (see Figure 1). It is 175 centimeters wide at the point where it connects to the body, and 100 centimeters wide at the point where it connects to the lower leg member, the tibia. The femur tapers down like this so as to make the entire leg, (i.e. both members), come to a point at the

foot. The actuators connect to the femur at approximately one third of the way in from each end. This was done so as to provide clearance for the lead screws of the actuators. The upper actuator is above the reference line connecting the femur's endpoints to provide for the proper angular displacement with a three meter leadscrew length. Similarly, the lower actuator is below the reference line to provide for the proper angular displacement of the tibia.

In order to make the femur very stable, all polygons in the space truss were removed by cross members. Therefore, the femur is entirely composed of triangular segments. This provides many stable shear planes to absorb torques imposed on the leg. Of particular interest is the member which goes from one actuator connect point to the other. This member provides an excellent path for force transmission from the foot of the leg to the body of the skitter since a lead screw will be at each end of this member.

The lower leg member, the tibia, is of a similar space truss design but has only 14 members (see Figure 2). Similarly, it is comprised entirely of triangular segments. The actuator connect point is above the reference line between endpoints to provide for clearance of the actuator leadscrew and to place the outer member in compression when the skitter is used as an outrigger for the crane.

The struts composing the skitter body and legs are constructed of a woven boron/epoxy composite with a honeycomb

core. Due to material and weight savings, the members are tubes with a circular cross-section. The tube ends are bonded to semi-circular stepped titanium splice fittings and then bolted to titanium end joints with steel bolts, thus providing a reliable connection. The struts will have a plastic or ceramic coating to protect the composite from the lunar environment. On top of this coating, a reflective coating will be applied to the struts to reduce the struts transmissivity and absorptivity of incident radiative energy.

The joints used at the femur-body and femur-tibia interfaces will provide for angular motion of the individual leg members with respect to each other and the skitter main body, and transmit axial and radial forces encountered during operation of the skitter (see Figure 3). These joints will be comprised of a pin joint supported by a combination thrust/journal bearing. A pin attached to one leg member will pass through a metal cylinder attached to the other leg member or the skitter main body. A solid lubricating Teflon™ based bearing material will be present at the rotating interface between the pin and the cylinder to create a low friction, tough, impact absorbing, and low wear joint. Resistance to contamination will be provided by labyrinth seals and wipers placed at the entry points of the pin into the cylinder and a flexible dust boot over the entire joint.

The actuators that power the legs will be six identical reciprocating ball screw linear actuators. They will have a stroke of three meters, and will be powered by eight horsepower

electric motors. The braking/holding system and position indicators will be an integral part of the actuator motor housing. The braking/holding system is required because the actuators by themselves are not self-locking. The position indicators will be required by the controls system which will coordinate the movement of the three legs to obtain the desired motion of the skitter. However, as the controls system evolves, it may be found that a velocity or acceleration indicator may be more useful and a reduced order observer could be used to reconstruct the remaining state variables.

The actuator will be mounted by the use of trunnion pins and a titanium collar, allowing the actuator to swivel as necessary during leg member movement. The actuator motor and gearbox for the femur-body actuator will be mounted on the femur. The leadscrew will be pinned to the skitter body (see Figure 6). This was done to avoid leadscrew interference at the top of the skitter. The triangular area that passes through the center of the body must remain clear at all times because that is part of the operating envelope for the various implements. Also, the crane will attach to the top of the skitter. The other end of the leadscrew at times will enter the space truss of the femur but has clearance at all times. The motor and gearbox for the femur-tibia actuator will be mounted on the tibia. This leadscrew will be pinned to the femur and the other end will operate in an area outboard of the tibia. This requires a slightly larger clearance area around the skitter itself but was

deemed to be acceptable.

A wiper is mounted internally to the actuator gear box to keep the screw clean and abrasive material out of the driving balls. The screw will also be enclosed in a concentric, spiral-wound metal cover to protect the screw and driver from the lunar environment. This was used rather than a rubber boot because the lead screw tends to "grab" the boot and pull it to one end during actuator motion, causing much damage to the boot.

Electrical power for the actuators and skitter support systems will be provided by a modified Space Shuttle fuel cell. The fuel cell is powered by the combining of Hydrogen and Oxygen in an exothermic chemical reaction. The product of this reaction is fresh water, which will be collected in an onboard retention tank for later transfer to the moon station module and eventual potable water use.

The foot, still in its conceptual stage, will be attached to the bottom of the tibia by a titanium block (see Figure 5). The three members will be placed into holes in the block and bolted in. Around this block will be semicircular rings, giving the foot a somewhat spherical appearance. This foot design was used because the angle between the tibia and the lunar surface will vary widely and the spherical shape gives the foot an optimal footprint regardless of the relative angle. Also, the semicircular rings will have some sort of "cleats" attached so as to improve the traction of the foot. This design also provides for a very stiff foot to ground interface which will be required

for the close tolerances needed by the drilling implement.

ANALYSIS

Introduction

Before an analysis of the skitter leg design is presented, it is necessary to acquaint the reader with the lunar environment in which it will be operating. This will provide the reader with a better understanding of the motivation behind some of the design decisions.

The lunar environment is an extremely alien one, one which the human body is not well adapted to surviving in. Besides the obvious lack of an atmosphere, there are many other factors of the environment which enter into the human factors of any design made for use on the lunar surface.

The moon has primarily a dark grey rocky surface and is approximately 4.2-4.3 billion years old. Some of the lunar soils are a little lighter since these were blasted up from the crust. The moon is composed primarily of silicate materials, with smaller amounts of many metal oxides. Most of the moon is composed of rocky layers with a very thin layer of soil, typically one half inch deep. There are many impacts on the surface, some filled in with lava from ancient volcanic activity. However, now there are no more major impacts since this part of the galaxy has been "cleaned up".

There is some seismic activity on the moon, but it is of little concern since there is little surface motion. The quakes are caused by the tidal influence of Earth which deforms the

rocky material of the core. It is widely believed that the surface motion is not great because the moon has a solid core, unlike the Earth.

The moon's surface is exposed to hard vacuum because there are only trace amounts of various gases. These gases, primarily hydrogen, nitrogen, argon, and helium are captured from the solar wind by the moon's gravitational field. More of these gases are present on the dark side of the moon. Because of the lack of an atmosphere, the lighting on the moon is very harsh due to no diffusion taking place. This causes pitch black shadows to occur on one side of an object and the other side to be brilliantly lit by the light from the sun. This calls for artificial lighting of any work area due to the danger of obstacles or holes being where lunar workers could not see. Also, the temperature differential on an object can be up to 400 °F due to this same problem. This is because the daytime side of the moon is usually $200^{\circ}\text{F} \pm 15^{\circ}\text{F}$ and the nighttime side is usually -200°F .

Another problem caused by no atmosphere is that there is no transmission of sound. Any communications on a lunar site will have to be by radio.

Leg Shape

In coming up with the design for the leg, the first factor that was considered was the optimum ratio of the lengths of the femur and tibia to the total length. It was apparent that it would be close to a 50/50 ratio. Since the upper joint is above

the usable sweep area for the leg, the ratio would be a little different though.

A program was developed that plotted the path that the end of the leg took as the tibia was swept through its full travel. Then the femur was incremented a set number of degrees and the tibia was swept once again (see Appendices 3b, 4a). Using this program, a ratio of 42/58 was chosen. This gave the leg a full length of 8.33 meters, 3.5 meters for the femur and 4.83 meters for the tibia. However, this path gave the largest envelope possible for the leg. It did not account for the fact that the legs angular displacements would be limited by actuator length. Therefore, after the actuator length was calculated (see actuator analysis), the program was ran again with the actuator constraints. The optimum ratio for the leg members then became 50/50. This gave the leg a full length of 8.5 meters, with 4.25 meters for each leg segment (see Figure 7 and Appendix 3a).

Because of the configuration of the joints, it can be shown that any point in the sweep area can be reached from any other point in the sweep area along any arbitrary path that remains in the sweep area. Since this is true, the sweep area also will show you the maximum vertical stroke obtainable at any given foot position. For example, looking at Figure 7, when the foot is five meters away from the body joint, the vertical stroke obtainable is from zero to five meters off the ground. Also, it can be seen that the maximum height of the skitter above the ground is now approximately 5.3 meters when the legs are extended

approximately 3.5 meters. As listed in the problem statement, a maximum height of six meters was desired. However, the small change in maximum height caused by adding the actuator travel limit was considered inconsequential.

In deciding how to size the members of the leg, the forces imposed on the frame by the different implements were researched. The soil bagger will place minimal loads of an undetermined amount on the skitter. The driller will place approximately 20 Nm of torque on each leg as calculated by the driller group. This also is a very small amount. The digger will primarily introduce downward forces while digging, but these were also of an undetermined amount. However, it became apparent after analyzing the crane loads that they are the most limiting factor in sizing the members of the legs (see Appendix 1a). The desired crane capacity is 4000 moon pounds, and the amount calculated to tip the skitter when the load is directly over one of the legs is 6140 moon pounds. This load must be raised to an angle of approximately 62° to prevent tipping when the load is rotated so that it is between two legs. The load that can be lifted with no regard to how far the load is from the center of the skitter is 428 moon pounds. The torque generated by the crane was small, 57 N per leg when the legs are in the outrigger position (see Appendix 1b). This is much more than the drill generates, however.

The normal force on the leg under the load just before tipping is then 7140 moon pounds, which is the weight of the

skitter and the load. Using this force, the reaction forces on the legs and actuators were calculated (see Appendix 1c). The force on the upper actuator, 142,500 N, played a major role in the actuator design. The magnitude of the body force, 142,350 N, was used in verifying that the Teflon™ bearings would withstand the load (see Appendix 1e).

It was desired to perform a truss analysis and obtain the individual forces on each member in the legs, but there was not enough time to do this. Instead, the forces in the three lower members were found and a buckling analysis of the members in compression was performed (see Appendix 1d). An isotropic modulus of elasticity was found for the boron/epoxy composite and using this value in the buckling formulas an outside diameter of 2.64" was calculated. The wall thickness was assumed to be one tenth of the outside diameter. Using the thickness calculated for buckling considerations, the static stress of the members in tension was calculated. The stress was much less than the yield strength of the boron/epoxy (see Appendix 1d).

Material Selection

Composites were considered for this project due to their light weight and high strength. Through continued research, the feasibility of composites in space applications has become apparent. A boron/epoxy composite was chosen for these reasons and for its material properties.

The boron/epoxy structure can operate in the large

temperature gradient of space without affecting the integrity of the material properties. Also, once cured, the structure should not fail when operated within the design parameters. In fact, the weakest part of the structure will be the joints. It is for this reason that a titanium joint that is bonded to and co-cured with the boron/epoxy tubes was chosen.

Once the leg was designed, the tube diameter was computed from buckling formulas, and found to be 2.64" outer diameter with a 2.37" inner diameter. Because the tube wall is fairly thick, 0.27", it was decided that there would be a honeycomb core of 0.172" sandwiched between the boron/epoxy walls (see Figure 4). This is allowable because the central layers of the composite would not carry a load in such a wall. The honeycomb core provides a weight and cost savings as well as adding some extra strength in the direction of the honeycombs.

The boron/epoxy tubes are fabricated by a process used by Grumman Aerospace Corporation in which the plies are convolute wrapped on a male mandrel, transferred to a female mold, and then autoclave cured. Transferring to a female mold eliminates fiber wrinkling and residual fiber stresses which occur in parts cured on a male mandrel. The plies are made of a woven boron, which provides an isotropic material. The titanium splice fittings are installed, then the boron/epoxy is wrapped over the splice fittings, completing the layup process. The tubes with the end fittings are then autoclave cured using the standard laminating cycle, and then oven post-cured, which completes the process.

The semi-circular splice fittings are then electron beam welded together, with the welding stopping approximately one half inch from the boron/epoxy which prevents overheating of the composite. The boron/epoxy tube with titanium end fitting is shown in Figure 8.

To assemble the skitter, the titanium end fittings are fitted over the titanium end plate and bolted with 220 HT steel bolts. This is demonstrated in Figure 9.

The extreme vacuum of space dries out composite materials which adversely affects their material properties. Therefore a surface coating to retard outgassing will be added. A plastic or ceramic coating can be used, and a plastic is recommended since it would be more durable.

Finally, to reflect solar radiation and keep parts from heating up, a coating such as aluminum plated mylar is applied to the structure.

Joints

Successful operation of the skitter in the lunar environment requires that suitable mechanical joints be designed and constructed. These joints will be needed to allow relative angular motion between leg components during movement and to transmit the forces that are encountered during normal operation. Before beginning the design, environmental demands and performance demands were determined to facilitate selection of joint type and materials. The severity of the lunar environment

demands the following of any joint design:

- protection from contamination
- functions over a wide temperature range
- indifference to radiation
- resistance to cold welding
- lubricant with a low vapor pressure
- thermal stability.

Some of the performance demands for the skitter joints are:

- high load capability
- impact resistance
- vibration damping
- dissipation of generated heat
- long life (i.e. low wear rate).

The difficulty of servicing the skitter in the lunar environment demands characteristics of the joints such as:

- high reliability
- simplicity
- self lubrication
- low wear of moving parts.

With these demands in mind, joint types and bearing configurations were evaluated to determine their suitability to the environment and task. Pin joints combined with journal/thrust bearings were selected because of their widespread

use and their general simplicity, reliability, and load carrying capability. These joints will be required at the point of connection between the skitter main body and the femur and between the femur and the tibia of each leg.

Joint structure material was considered based on the criteria of high strength and low weight. Materials that best meet these two criteria are aluminum, titanium or beryllium alloys. Titanium alloy construction was selected for the pin and joint cylinder because it may be bonded with the boron/epoxy composite material selected for the leg structure. *

Some form of lubrication will undoubtedly be needed to insure smooth operation of the joints. However, in the lunar environment atmospheric pressure is virtually zero (approx. 10^{-12} torr). This condition makes the use of traditional lubrication methods such as grease or oil impossible as their vapor pressures are much too high. Solid lubricants are a promising alternative because of their low vapor pressure, thermal stability, and resistance to radiation. Of the solid lubricants, metals were disregarded because of their generally poor wear resistance. Any solid lubricant must show extremely low wear in order to achieve the reliability and long life required of the joint. Elimination of the metallic solid lubricants leaves the plastics, thermoplastics, and the thermosetting resins as possible solid lubricant materials. The fluorocarbons are excellent materials for use in the lunar environment. PTFE, in particular, more commonly known by its trade name TeflonTM, possesses some of the

best properties of any non-metallic solid lubricant. Some of its properties include:

- lowest coefficient of friction of any plastic
- coefficient of friction inversely proportional to load
- excellent resistance to radiation (threshold of detectable damage is around 2×10^6 rad)
- low vapor pressure (1×10^{-16} atm at 260°F)
- self lubricating
- excellent heat resistance
- useful at low temperature
- shock resistant and vibration damping.

Disadvantages of PTFE include low thermal conductivity, low compressive strength, and high thermal expansion. However, these disadvantages can be overcome by modifying the virgin PTFE through special fabrication techniques and the addition of fillers. Based on the above information, PTFE will be utilized as a solid lubricating bearing material at the location of sliding contact between the pin and the joint cylinder.

There remain additional environmental and performance factors to be dealt with. The joint for the skitter will have to contend with potential contamination by lunar soil. Introduction of lunar soil into the area of sliding contact in the joint will adversely affect joint life. The use of labyrinth seals is a viable sealing method in journal bearings applications. Since the only mode of transport for lunar soil particles is their

kinetic motion, a labyrinth seal and a wiper combined with a flexible dust boot covering the joints will be used to protect the skitter joints from possible contamination.

Dissipation of heat generated in the joint by friction during sliding is another problem to be considered in the joint design. Temperature rise at the sliding interface will depend on load, friction coefficient, and thermal conductivity of the bearing material. Control of surface temperature is important because the Teflon™ will soften as its crystalline melting point is approached, resulting in a drastic increase in wear. The crystalline melting point of PTFE is 327°C. Selection of Teflon™ as bearing material will decrease the contribution to surface temperature by friction at the sliding interface because of its low friction coefficient, but will increase the contribution by thermal conductivity because of its low conductivity. The solution to this problem lies in the modification of the Teflon™ by addition of fillers and the utilization of some special fabrication techniques. A bronze impregnated, woven PTFE or PTFE impregnated bronze fiber will be utilized for bonding to the inside of the titanium joint cylinder as the bearing surface in the skitter joints. Heat generated at the sliding interface will be drawn off through the titanium alloy pin and the Teflon™ and bronze matrix, whose thermal conductivity is much greater than pure Teflon™.

The actual size and shape of the skitter joints will be determined by consideration of the desired angular velocity of

the legs, the maximum pressure that can be applied to the bearing material while holding wear rate to an acceptable level, and the expected worst case joint normal and axial loads. The recommended joint configuration will consist of a nominal 6 centimeter diameter titanium alloy pin attached to the skitter femur at three points, two at each corner and one in between, which will pass through the center of two titanium cylinders attached to the main body. The pin will be in contact with the interior of four TeflonTM fabricated cylinders, each approximately 30 centimeters in length and 2 centimeters in thickness, which are bonded to the inside of two titanium alloy cylinders. Thrust plates will be located at either end of the pin to transfer axial loads. Thus, the joint combines aspects of a pin connection and a journal bearing. A labyrinth seal will be created by the intermeshing of plates attached in an alternating manner to the pin and the cylinder at the entrance of the pin into the cylinder. A simple wiper will also be present at each entry point. Finally, a flexible dust boot will cover the entire joint assembly. A similar configuration will be used for the joint between the femur and tibia. A prototype skitter joint showing the above described features may be seen in Figure 3.

Actuators

The actuator size is dependent upon its placement on the legs. Placed close to the joint the actuator has a shorter stroke for the same amount of foot travel but this position also

increases the amount of axial force that the actuator must output.

The actuators are placed one third of the way down the length of each leg. Under worst case conditions, which is the crane lifting its maximum load over a leg, the actuator has an axial force of 31,000 pounds.

The foot has a maximum speed of 2.6 ft/sec to prevent tipping. An operational foot speed of 1.5 ft/sec was selected for this design. A foot speed of 1.5 ft/sec corresponds to an actuator speed of 30 ft/min.

The Duff-Norton Company manufactures a reciprocating ball screw actuator that meets these specifications. The screw is manufactured by Saginaw Products Corporation, with the gear box manufactured by Duff-Norton. The actuator has a safety factor of 1.1 and the driving motor is a 8 HP AC motor. This motor is manufactured by Reliance and comes with an internal brake, which is needed since the leadscrew is not self-locking. See Appendix 5 for the actuator specifications.

Power Supply

The skitter power supply must supply the needed electrical power for all onboard controllers and communication devices, as well as the actuators to move the skitter and the lights to allow operation in the dark or shadows.

The skitter will have 12 lights; 2 mounted on each side, one mounted on each femur and one mounted on each tibia.

The total continuous load will be 12 KW. This will power the lights, on board controllers and communication devices. Another 12 KW will be necessary to run all the actuators at once. The skitter will operate 10 hours per day with the actuators being energized for a total of one third of this time. This will allow 10 days of skitter operation between necessary refuelings.

The skitter will have onboard inverters to change the fuel cells DC current output to the required AC current for actuator operation.

The fuel cell will actually consist of three separate fuel cell power plants, four hydrogen storage tanks and four oxygen storage tanks.

Foot

In determining a material suitable for the skitter foot, several conditions must be met. First, under the extreme temperatures of the lunar environment the material should have similar thermal expansion characteristics as the leg material (boron/epoxy). After some study, it was determined that titanium or a titanium alloy was suitable for the application. The choice material is the titanium alloy ASTM 13265-58 T-5 since it has an advantageous extreme temperature strength. Mechanical and thermal properties are listed in Appendix 5.

Also important in material selection is a low density that will sustain large impacts as the skitter moves. Titanium fits this need well.

In the design of the foot, it is important that the foot provide the necessary surface contact for traction as the skitter moves and performs its necessary utilities. Also worth noting is that the foot will be contacting the surface at various angles. In order to meet this design need, the foot was envisioned to be concave toward the surface and titanium rod meshed.

The actual sizes of members is yet to be determined because the foot design was conceptualized later in the project. See Figure 5 for a conceptual drawing of the skitter foot.

Cost

Two costs were analyzed : the cost of materials and the cost of shipping (see Appendix 2). The cost of the materials for building the skitter was reasonable at approximately three quarters of a million dollars. However, the cost of shipping the skitter to the moon was unbelievably high, approximately 148 million dollars. This amount is too high and the weight of the skitter must be reduced to lower this. The two focus areas for weight reduction are the actuators and the power supply. This is discussed in other parts of the paper.

CONCLUSIONS AND RECOMMENDATIONS

The design of the leg satisfied many of the original design criteria with the exception of a few problems.

The material chosen, boron/epoxy composite, ended up being a wise choice as it provides much strength at a high strength to weight ratio. Weight appears to be a major concern as the cost of shipping the skitter to the moon dwarfs the other costs (see Appendix 2). However, other materials such as boron/aluminum could be considered. Also, at the very end of the project an unpublished technical paper was received from Mr. Richard Hadcock of Grumman Aerospace Corporation. This paper has information on optimizing the composite geometry that will be of interest to future groups.

The truss design appears to be able to withstand the loads that will be imposed on the frame. However, more analysis needs to be performed as only the lower three members were analyzed due to lack of time. Even if other members need to be sized larger, the magnitudes of the external forces and the relative lengths of the members suggest that the change will be small. Also, putting the leg on a structural design program such as GTSTRUDL would enable one to analyze many different configurations for the leg under many different loading conditions. Doing this would possibly enable the elimination of some of the members, which would save weight. Also, fatigue analysis of the skitter frame needs to be performed because fatigue will be an important factor

due to the way that the skitter is designed to move. This analysis needs to be performed later when more data concerning the operating cycle of the skitter is known.

One area that needs more investigation is the actuator. With the present configuration, a very large actuator is required during operation of the skitter as an outrigger for the crane. The cost of shipping these actuators to the moon is very high and it is evident that lighter ones will have to be used. Also, the power requirement is too high since the motor required is one which will drive the actuator at rated load. Reducing the power requirement will also enable the use of a lighter power supply, allowing further savings on shipping costs. The Duff-Norton actuators are designed to move at rated load which is the reason such a large actuator was chosen. Duff-Norton stated that if an actuator was needed that did not have to move at the rated load of the leadscrew, it would have to be designed since all of their off the shelf products are designed that way.

Possibly pinning the legs in the outrigger position would help alleviate this problem. Pinning the legs would take some or all of the force off of the actuator leadscrew. Then a smaller actuator could be used since it would not have to withstand as high a force. This is feasible since the legs do not need to move while in the outrigger position. Then after the crane was through moving objects, the legs could be unpinned.

Another possible way to be able to use a smaller actuator is to move the actuator connect points so the actuators "see" a

smaller force. However, the leg operating envelope must be kept in mind when this is performed.

The foot concept holds promise as it solves the problem of providing traction at all of the leg angles without having any moving parts, thus improving reliability. All of the forces, etc., still remain to be calculated on it.

The pin joint at the leg joints is very simple and thus very reliable. This is very important because reliability is a prime consideration when operating in the lunar environment. Also, Teflon™ as a lubricant should give trouble free operation.

ACKNOWLEDGEMENTS

The SKITTER group would like to gratefully thank the following people who provided us with valuable information and insight into the problem at hand. Without their help the project would not have been a success.

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Advanced Development Dept. Bethpage, NY

(516) 575-0574

Mr. Don Kuehl, Composites Incorporated, (203) 649-2923

Mr. Brice MacLaren, Mechanical Engineering, Georgia Tech

Mr. Gary McMurray, Mechanical Engineering, Georgia Tech

Dr. G.J. Simitzes, Aerospace Engineering, Georgia Tech

Dr. Ward O. Winer, Mechanical Engineering, Georgia Tech

Mr. Curtis Wright, Engineer, Duff-Norton

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FIGURES

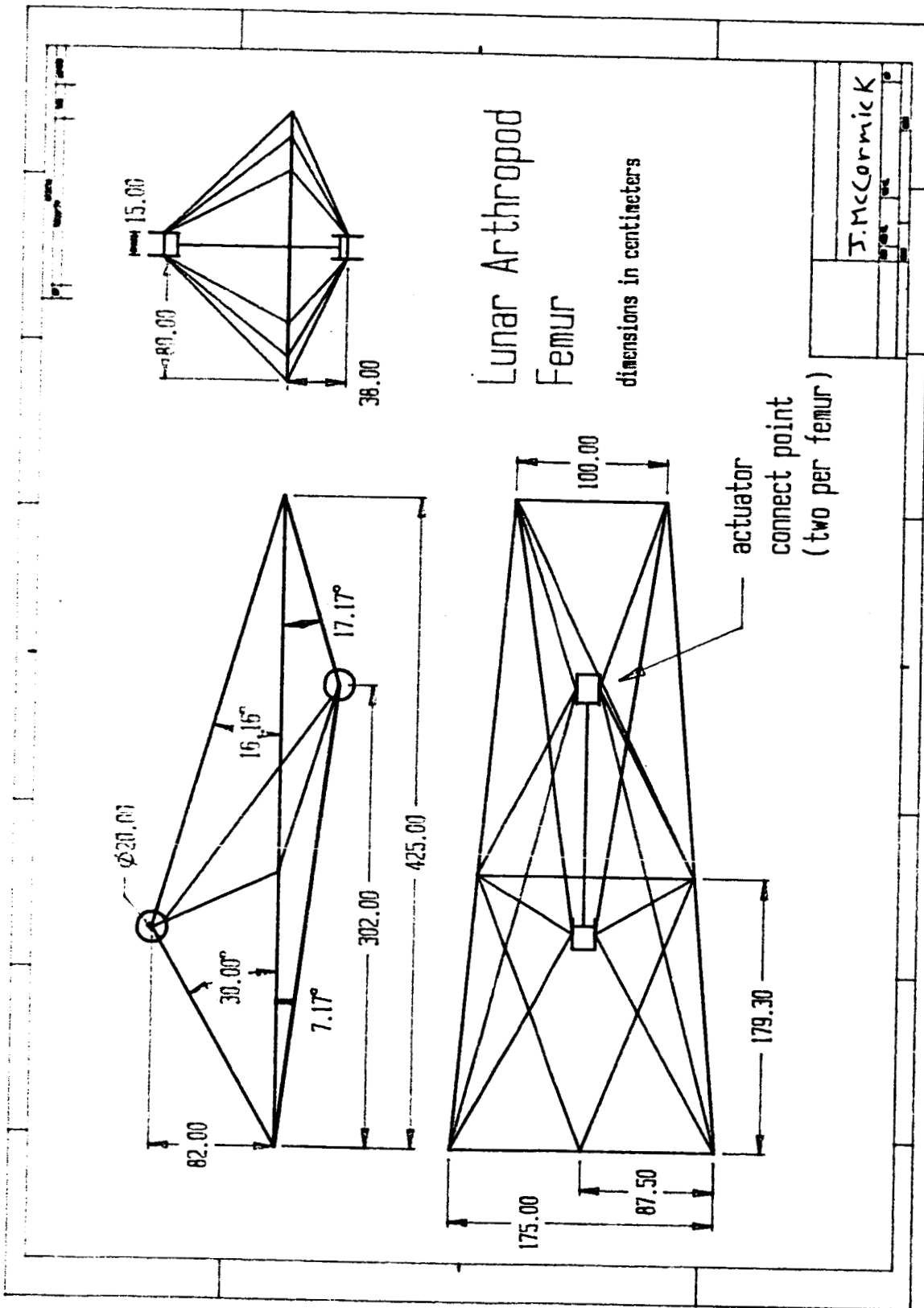


Figure 1

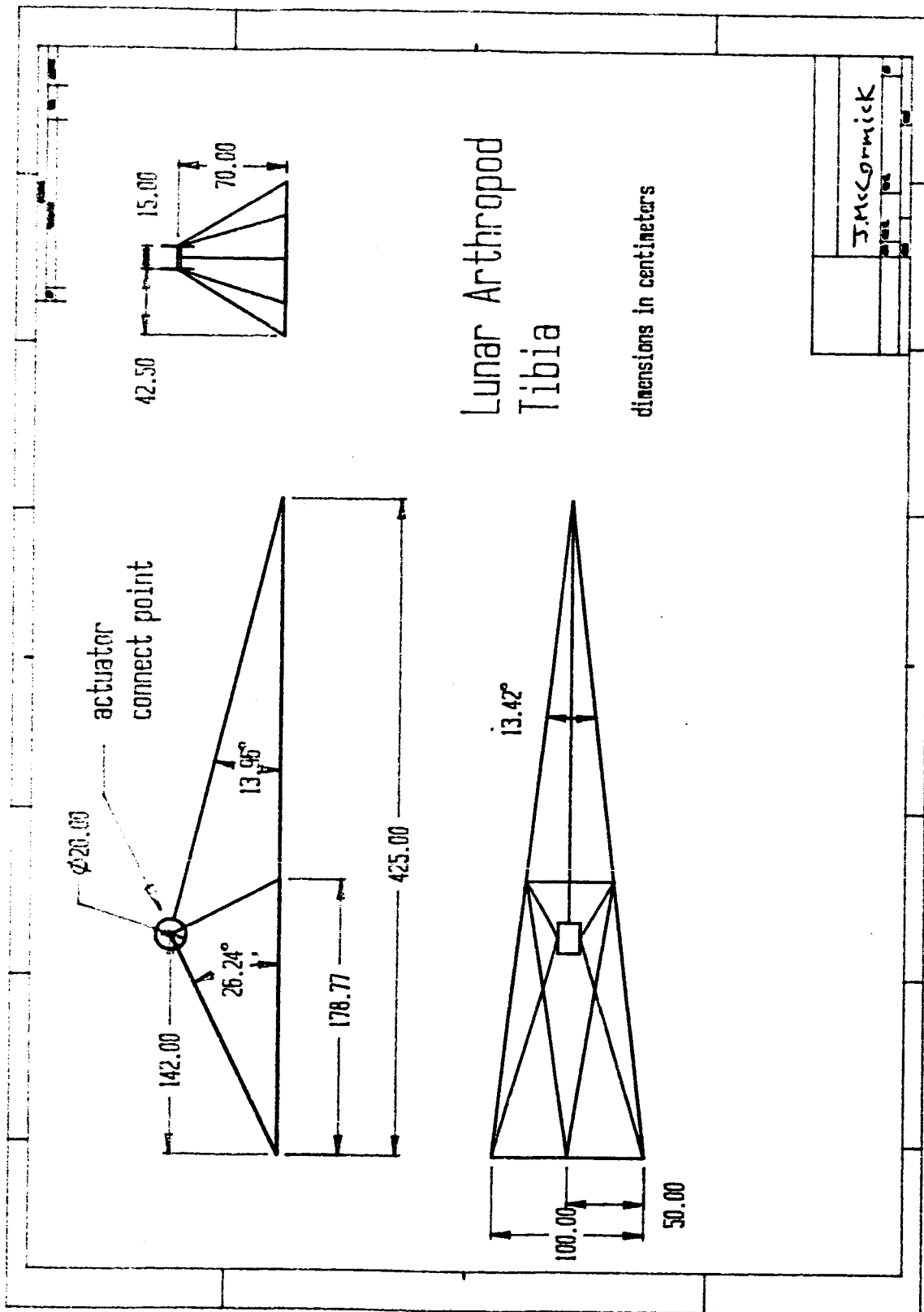
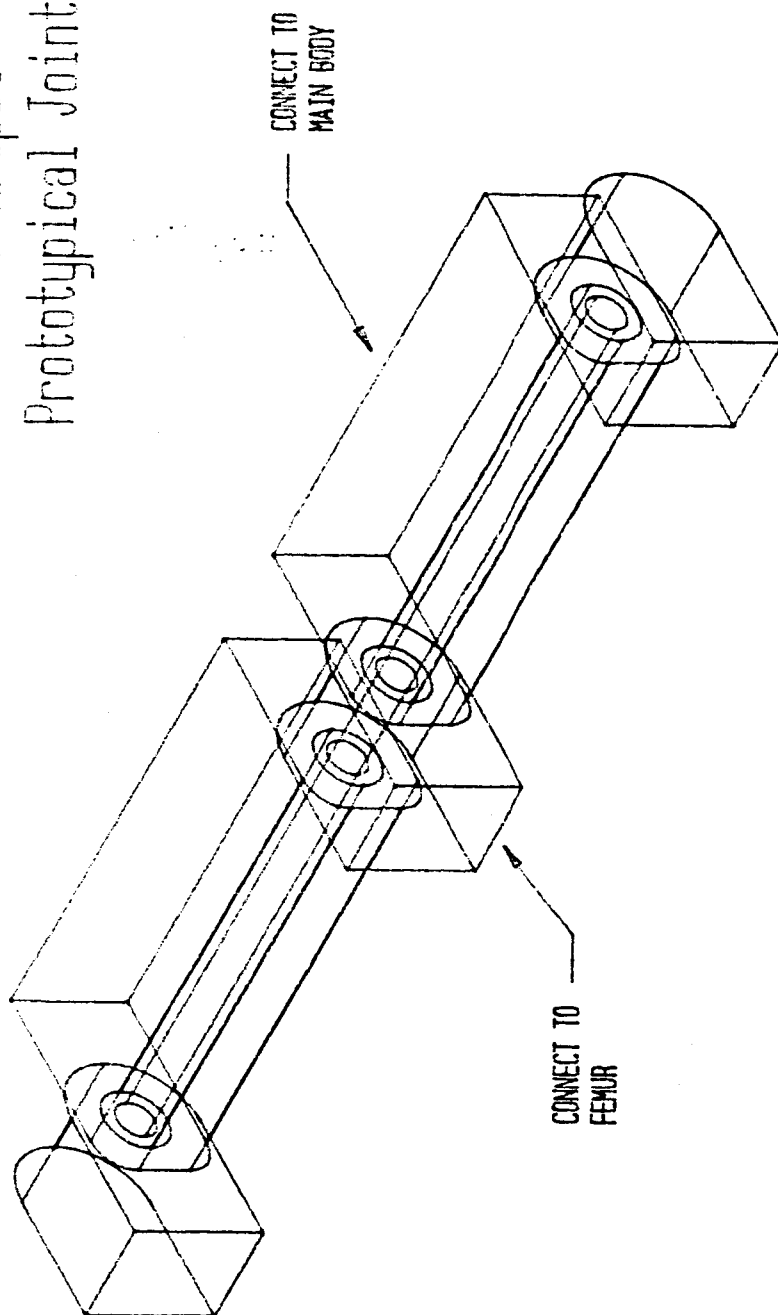


Figure 2

Lunar Arthropod Prototypical Joint



J. McCormick

Figure 3

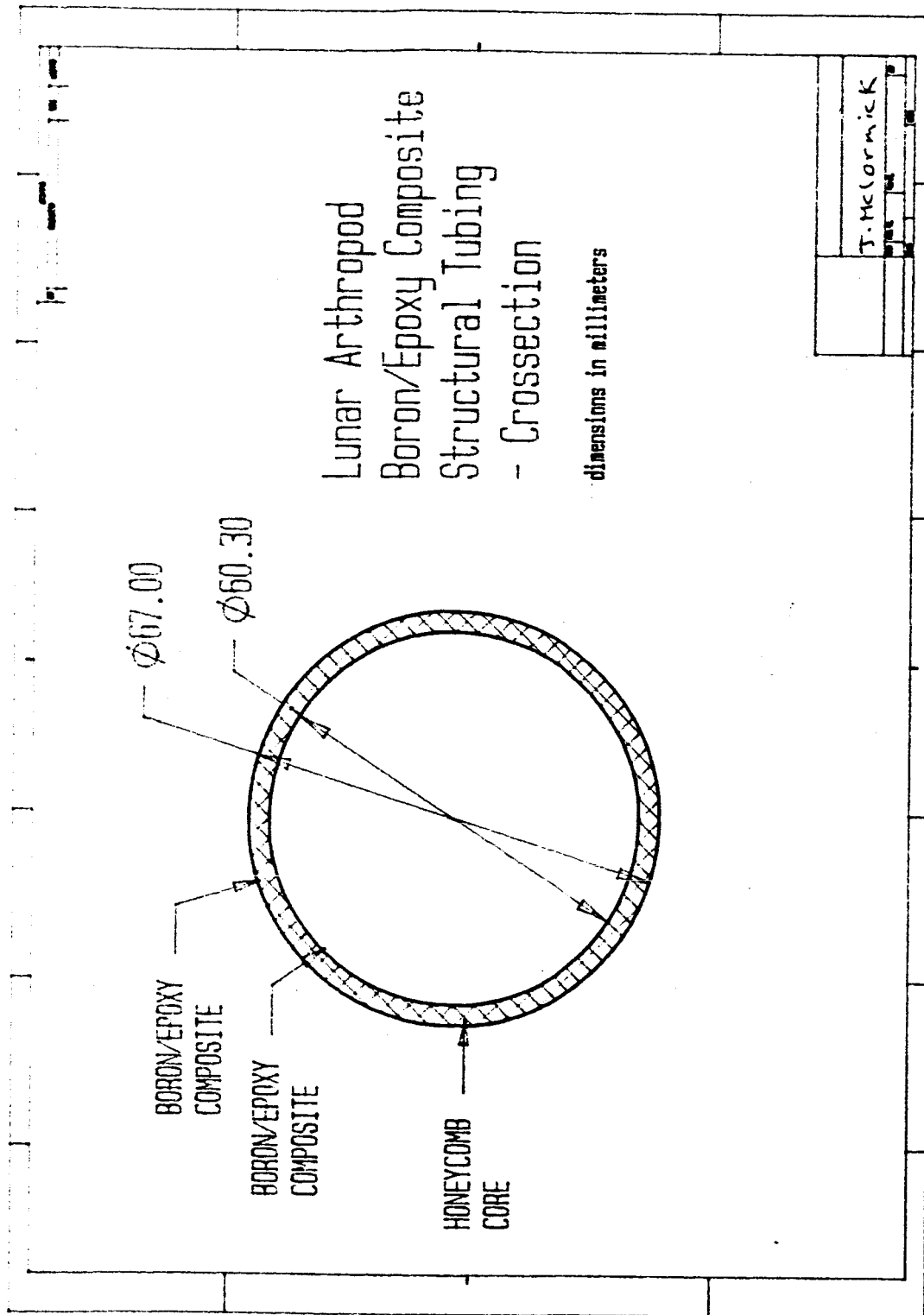


Figure 4

Lunar Arthropod Conceptual Foot Design

J. McCormick

TIBIA STRUCTURAL
TUBE AXES

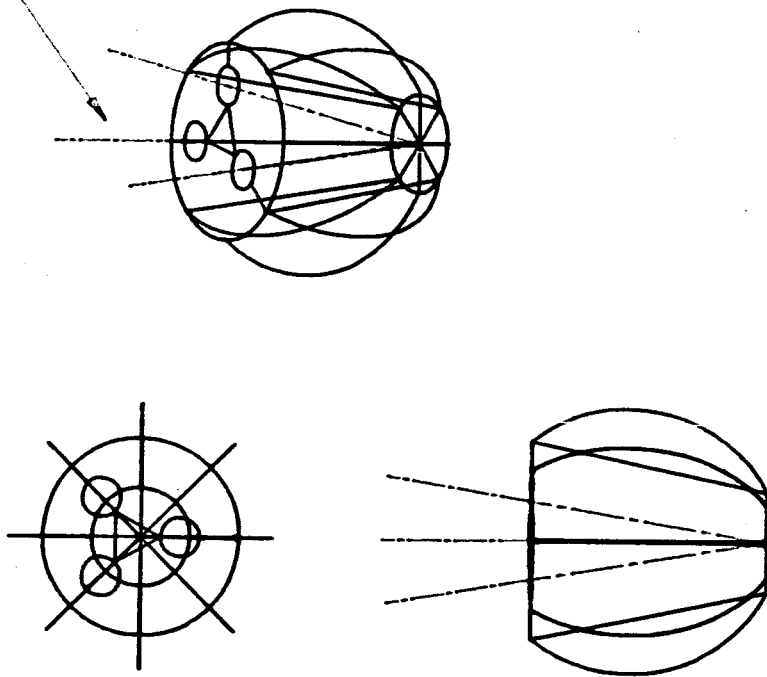
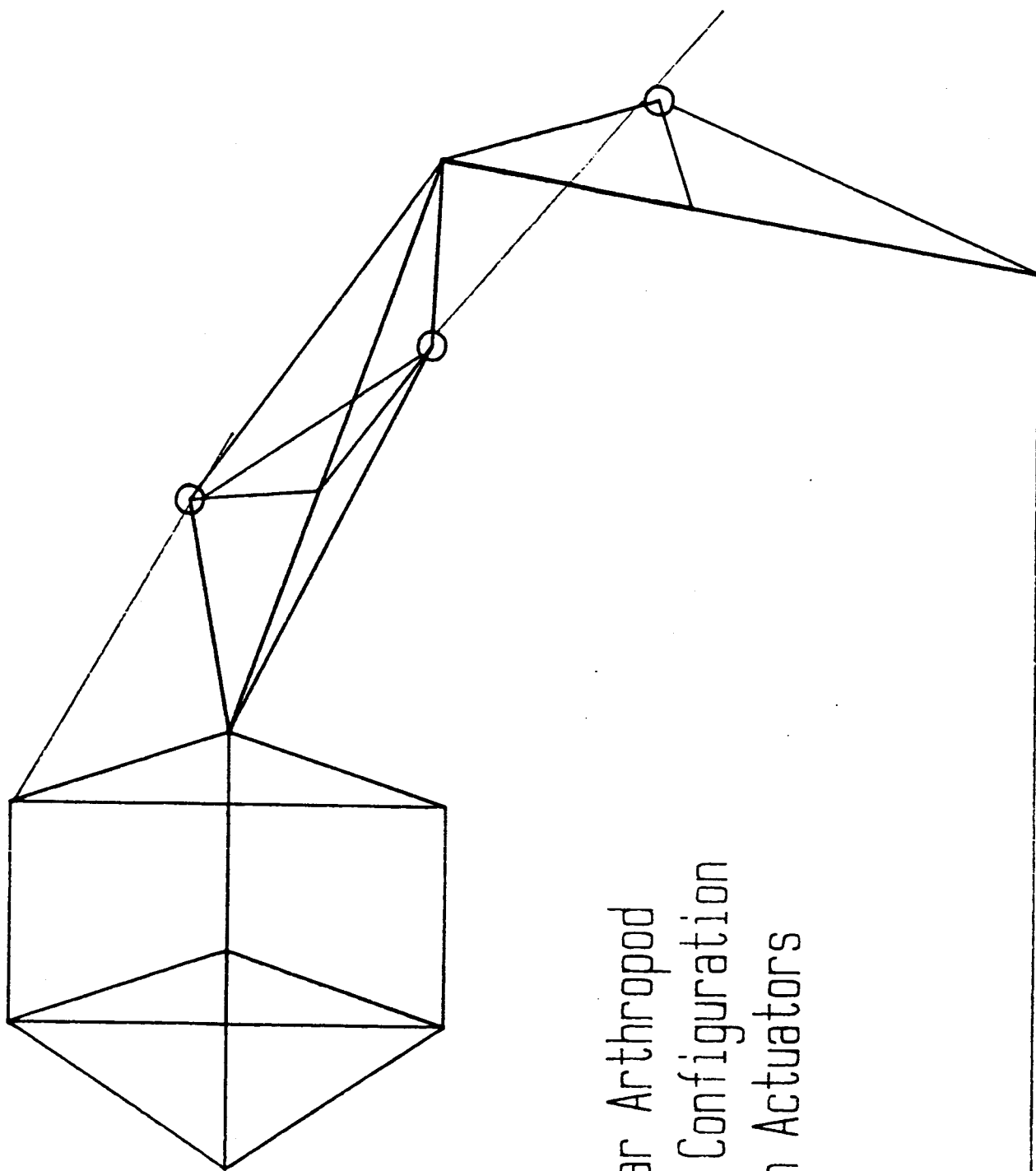


Figure 5

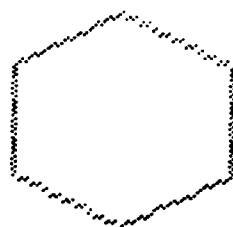


Lunar Arthropod
Leg Configuration
With Actuators

Figure 6

| | | | |
|-------|-------|------|----|
| Femur | (50%) | 4.25 | m. |
| Tibia | (50%) | 4.25 | m. |
| Total | | 8.50 | m. |

Skitter
height
above
ground :



6.00 meters

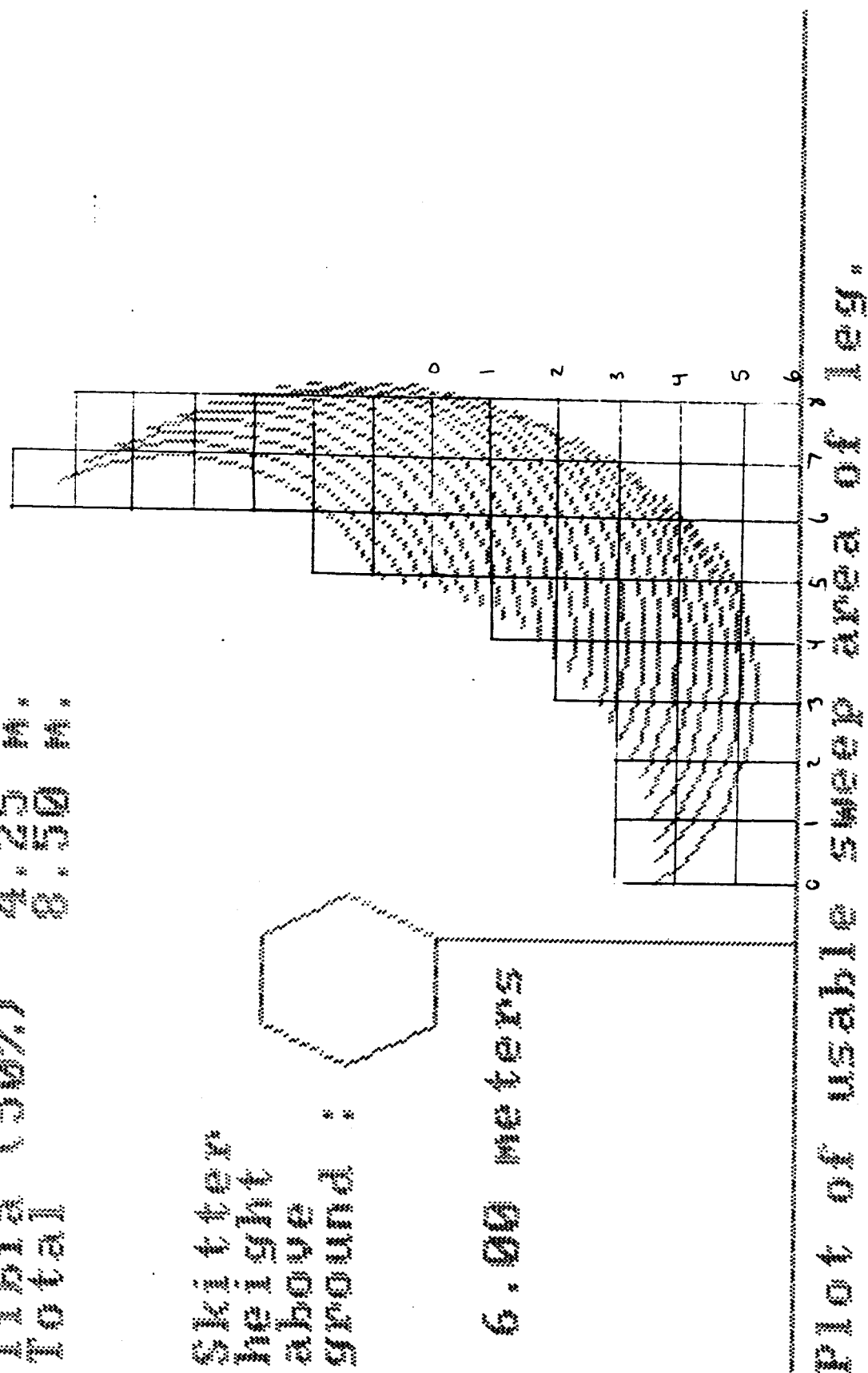


Figure 7

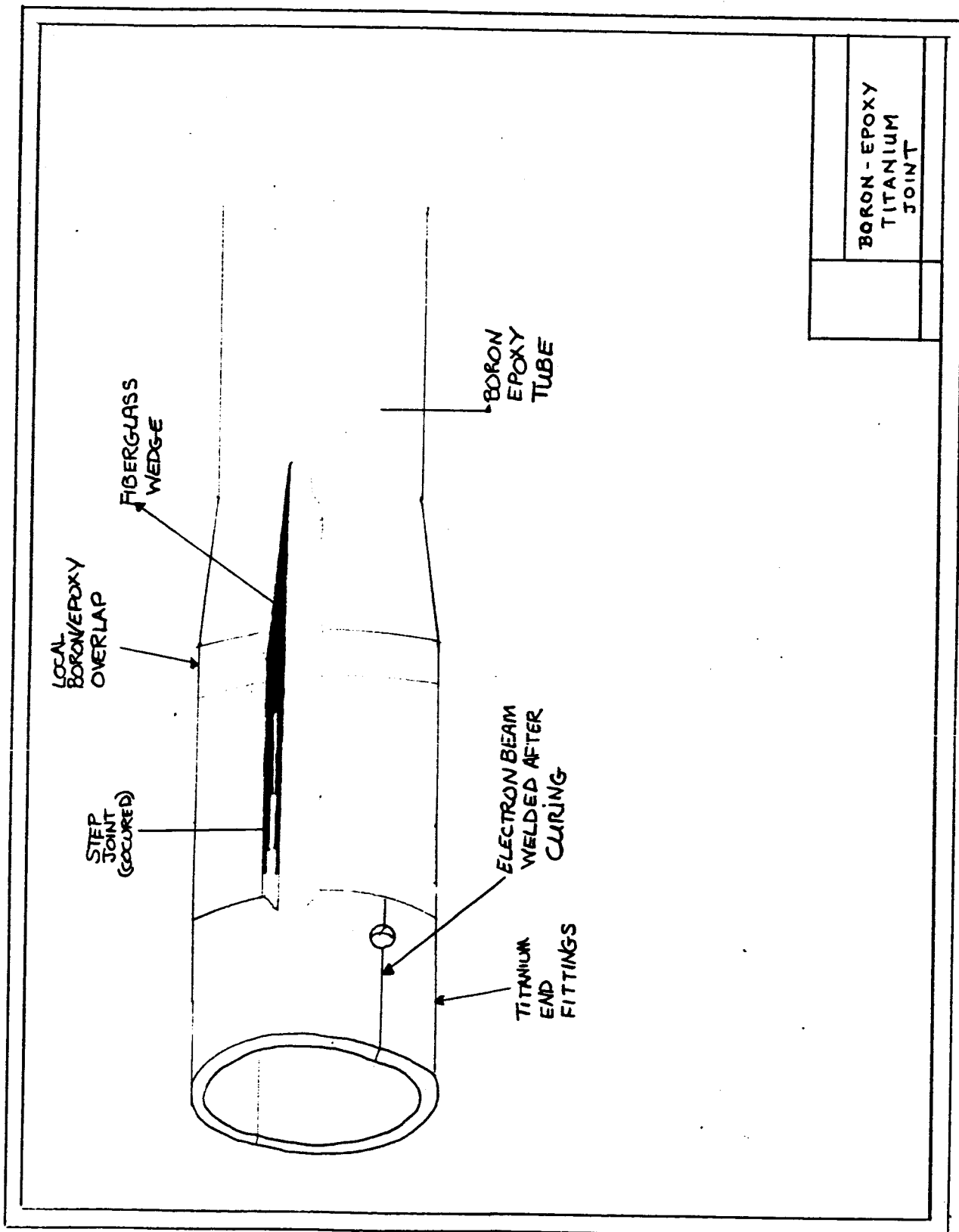
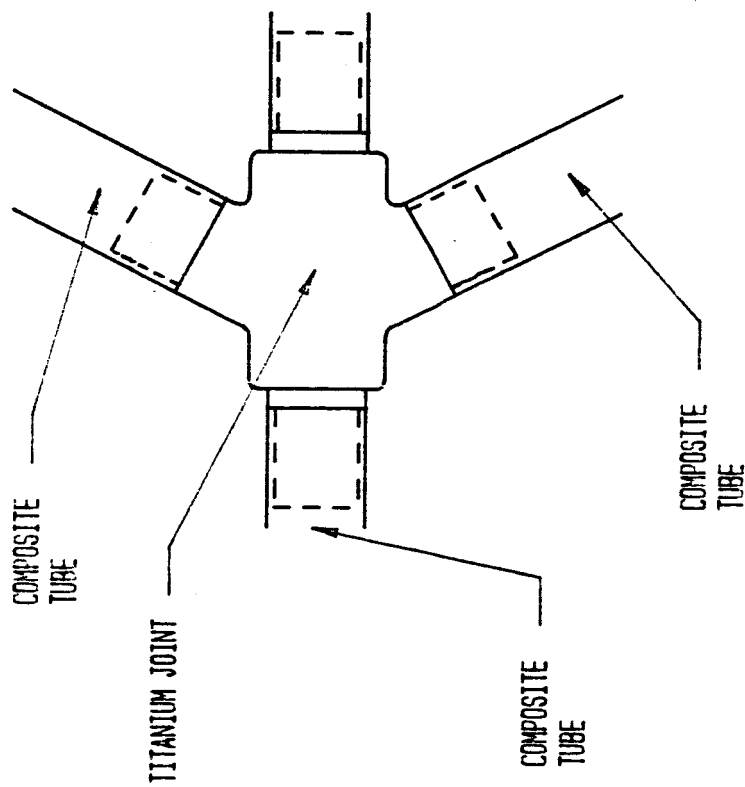


Figure 8

Sample Composite Structural Tubing Connection



J. McComick

Figure 9

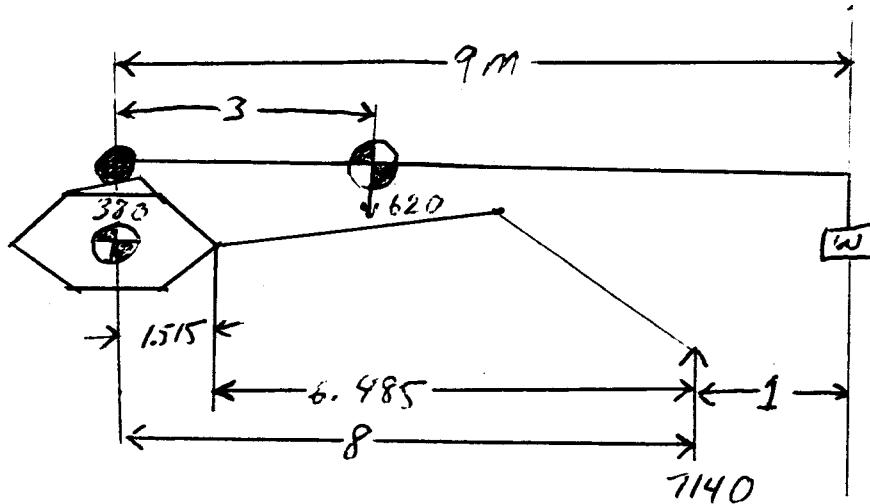
APPENDICES

Appendix 1 Calculations

Appendix 1A Crane Capacity Calculations

CRANE CAPACITY

(ALL WEIGHTS ARE IN MOON POUNDS)
(ALL LENGTHS ARE IN METERS)



AT POINT OF TIPPING WITH CRANE DIRECTLY OVER THE LEG

$$380(8) + 620(5) = W$$

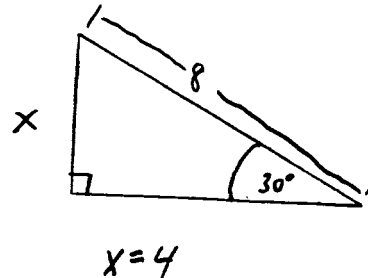
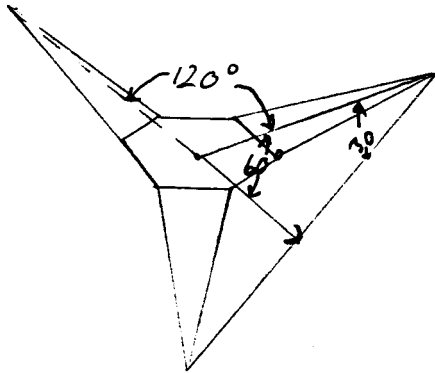
$$W = 6140$$

MAX CRANE CAPACITY IS
4000 POUNDS.
FACTOR OF SAFETY = 1.535

ASSUMPTIONS

- 1) CRANE WEIGHT = 620 POUNDS
- 2) ASSUME CRANE CM 3m OUT
- 3) 72.06% OF FULL LEG EXTENSION
 $(9)(.7206) = 6.485$
- 4) CRANE IS DIRECTLY OVER THE LEG

CRANE IS LOCATED MID-WAY
BETWEEN THE LEGS



CALCULATE NEW MAX WEIGHT

$$(380)(4) + (620)(1) = 5W$$

$$W = 428.16$$

with factor of safety = 1.535

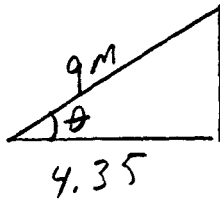
$$\underline{\text{max weight} = 279.16}$$

RATIO OF MOMENTS

$$(5)(428) = (6140)x$$

$$x = .3485 \text{ m}$$

HAVE TO BRING THE MAX LOAD (6140 LB)
IN TO WITHIN $4 + 0.3485 = 4.35 \text{ m}$ OF
THE CENTER OF SKITTER TO MOVE THE
LOAD FROM OVER THE LEG.

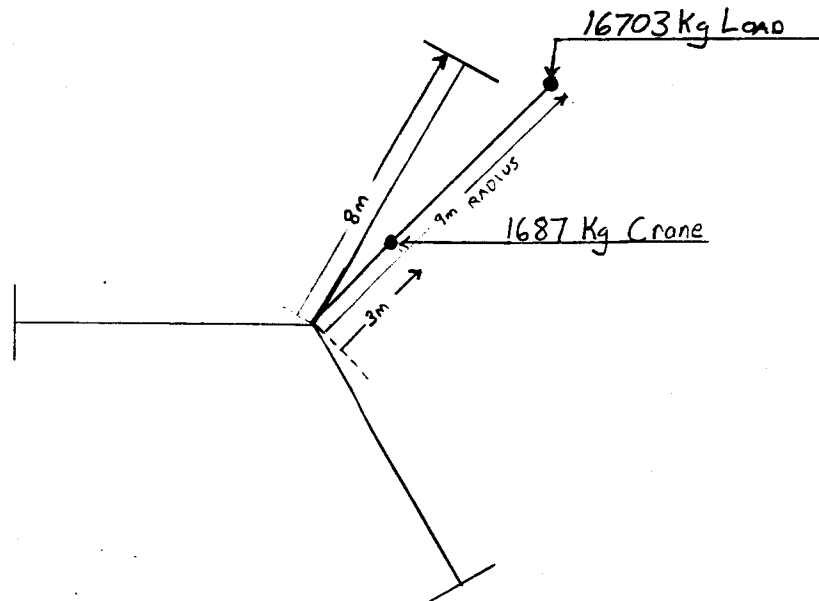


$$\theta = \cos^{-1} \left(\frac{4.35}{9} \right) = 61.1^\circ$$

MUST RAISE THE CRANE TO 62° ABOVE
THE HORIZONTAL TO SPIN IT AROUND

Appendix 1B Torque on Skitter from Crane

WORST CASE TORQUE ON SKITTER FROM CRANE



Assumptions:

- 1) $\alpha = 0.001 \frac{\text{rad}}{\text{sec}^2}$
- 2) $\omega = 0.033 \frac{\text{rad}}{\text{sec}}$
NOT LIMITING FOR TORQUE
EXCEPT THAT LOAD MAY
SWING OUT PAST CRITICAL RADIUS
- 3) $g_{\text{moon}} = 1.635 \frac{\text{m}}{\text{s}^2}$

LOAD MASS:

$$m_L = \frac{27310 \text{ N}}{1.635 \frac{\text{m}}{\text{s}^2}} = 16703 \text{ Kg}$$

CRANE MASS:

$$m_C = \frac{2758 \text{ N}}{1.635 \frac{\text{m}}{\text{s}^2}} = 1687 \text{ Kg}$$

Inertia:

$$\begin{aligned} I &= (3)^2(1687) + (9)^2(16703) \\ &= 15183 + 1352943 \\ I &= 1.368126 \times 10^6 \text{ m}^2 \text{ Kg} \end{aligned}$$

TORQUE:

$$\begin{aligned} T &= I\alpha \\ &= (1.368126 \times 10^6)(0.001) \\ T &= 1368.1 \text{ Nm} \end{aligned}$$

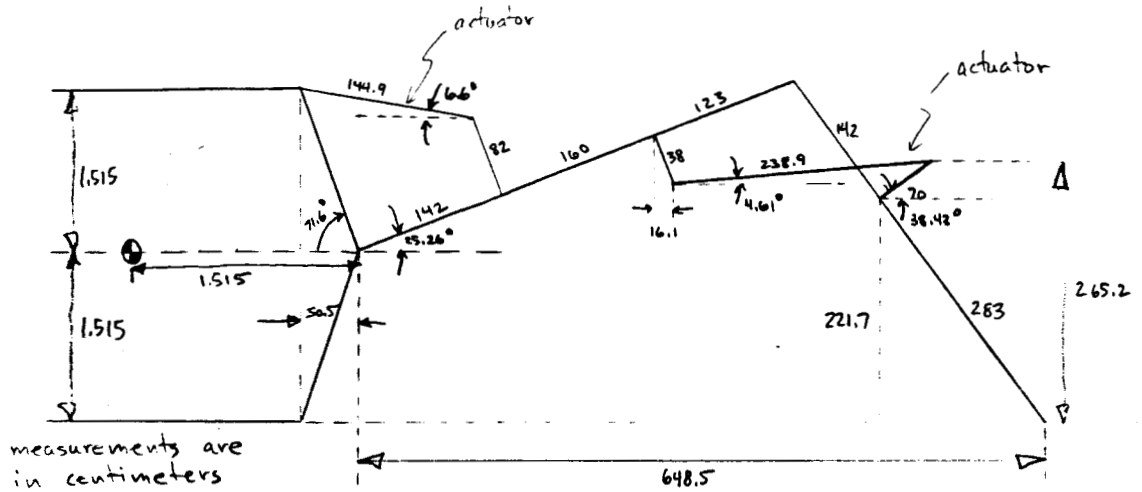
FORCE:

$$\begin{aligned} 3F_{\text{leg}} &= T/r \\ F_{\text{leg}} &= \frac{(1368.1)}{3(8)} = 57 \text{ N} \end{aligned}$$

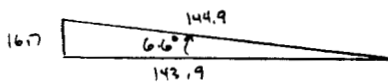
Appendix 1C Forces on Legs and Actuators

FORCE CALCULATIONS

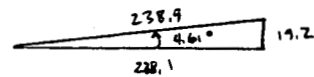
not drawn to scale



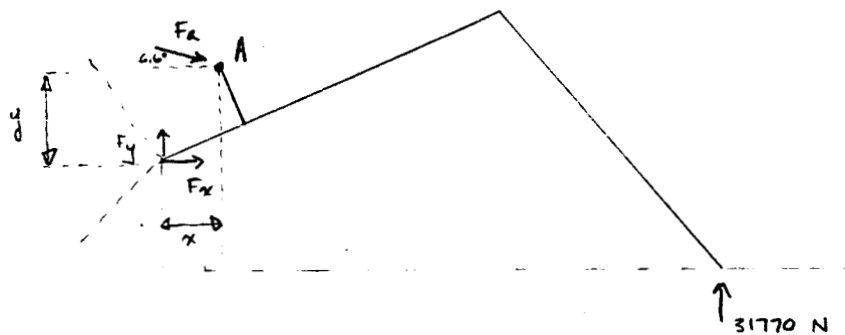
skitter-femur actuator



femur-tibia actuator



find force on skitter (just at point of tipping due to crane load)



$$\sum M_A = 0$$

$$x = 142 \cos 25.3 - 82 \sin 25.3 = 93.3$$

$$y = 142 \sin 25.3 + 82 \cos 25.3 = 134.8$$

$$31770 (555.17) + F_x (134.8) = F_y (93.3)$$

$$\sum F_x = 0$$

$$F_x = -F_a (\cos 6.6) = -0.9934 F_a$$

$$\sum F_y = 0$$

$$F_y = -31770 + F_a \sin 6.6 = -31770 + 0.1149 F_a$$

back to moment calculation

$$31770(555.1) - (0.9934)(134.8) F_a = 93.3(-31770 + 0.1149 F_a)$$

$$144.63 F_a = (31770)(648.4)$$

$$F_a = 142,430 \text{ N}$$

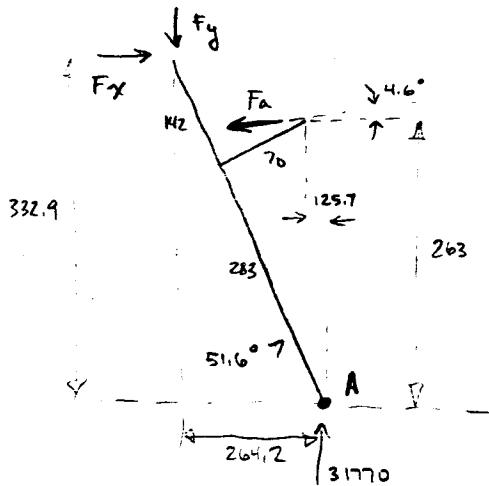
$$F_a \approx 142,500 \text{ N}$$

$$\therefore F_x \approx 141,500 \text{ N}$$

$$\therefore F_y \approx -15,500 \text{ N}$$

find forces on tibia

not drawn to scale



$$\sum M_A = 0$$

$$F_a [\underbrace{\cos 4.6(263) + \sin 4.6(125.7)}_{272.2}] + F_y(264.2) - F_x(332.9) = 0$$

$$\underline{\Sigma F_y = 0}$$

$$F_a (\underbrace{\sin 4.6}_{0.080}) + F_y = 31770$$

$$\underline{\Sigma F_x = 0}$$

$$\frac{F_a (\cos 4.6)}{0.997} - F_x = 0$$

$$\begin{bmatrix} 272.2 & 264.2 & -332.9 \\ 0.08 & 1 & 0 \\ 0.997 & 0 & -1 \end{bmatrix} \begin{Bmatrix} F_a \\ F_y \\ F_x \end{Bmatrix} = \begin{Bmatrix} 0 \\ 31770 \\ 0 \end{Bmatrix}$$

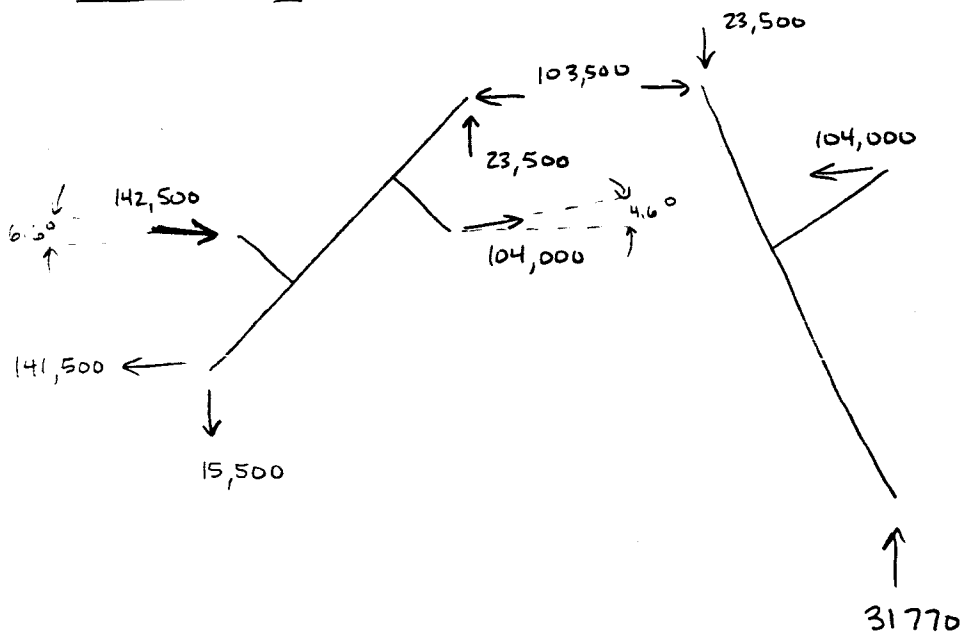
solving,

$$F_a \approx 104,000 \text{ N}$$

$$F_y \approx 23,500 \text{ N}$$

$$F_x \approx 103,500 \text{ N}$$

Summary



all forces are in Newtons

Appendix 1D Stress and Buckling of Lower Leg

ANALYSIS OF LOWER TIBIA MEMBERS.

All angles in Degrees.

Directions of 3 lower Tibia Members:

$$\textcircled{1} D_1 = \cos(65^\circ) \hat{i} + \sin(65^\circ) \hat{j}$$

$$\hat{D}_1 = .41422 \hat{i} + .91018 \hat{j}$$

$$\textcircled{2} D_2 = \cos(52^\circ) \hat{i} + \sin(52^\circ) \hat{j} - \sin(7^\circ) \hat{k}$$

$$D_2 = .62156 \hat{i} + .78337 \hat{j} + .11684 \hat{k}$$

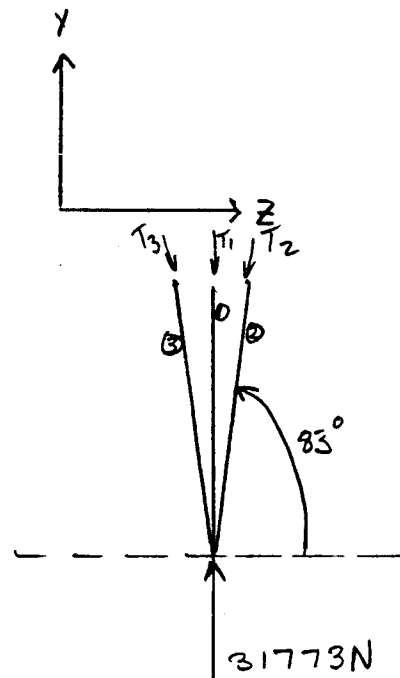
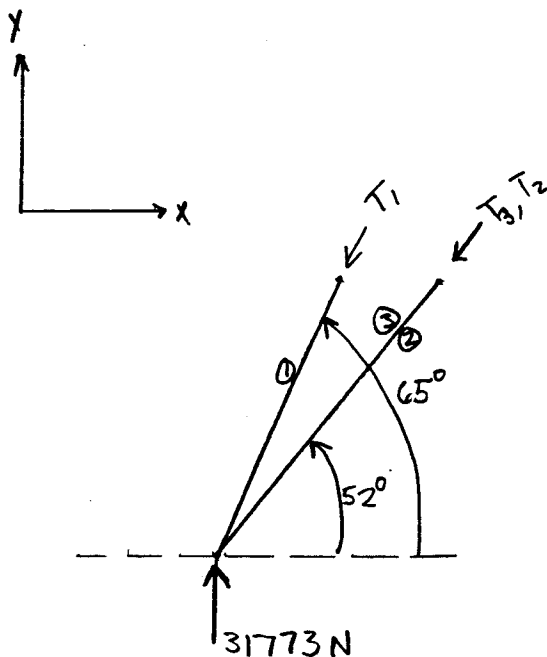
$$|D_2| = 1.00680$$

$$\hat{D}_2 = .61736 \hat{i} + .77808 \hat{j} + .11605 \hat{k}$$

\textcircled{3} By symmetry to direction \textcircled{2}

$$\hat{D}_3 = .61736 \hat{i} + .77808 \hat{j} - .11605 \hat{k}$$

Force From Ground = 31773 N



Sum forces in x, y, and z directions:

$$\Sigma F_x = T_1(.41422) + T_2(.61736) + T_3(.61736) = 0$$

$$\Sigma F_y = T_1(.91018) + T_2(.77808) + T_3(.77808) = 31773$$

$$\Sigma F_z = T_2(.11605) - T_3(.11605) = 0$$

$$T_2 - T_3 = 0$$

$$\begin{pmatrix} .41422 & .61736 & .61736 \\ .91018 & .77808 & .77808 \\ 0 & 1 & -1 \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} = \begin{pmatrix} 0 \\ 31773 \\ 0 \end{pmatrix}$$

$$T_1 = 81863 \text{ N}$$

$$T_2 = -27463 \text{ N}$$

$$T_3 = -27463 \text{ N}$$

Members T_2 and T_3 are in Tension.

Member T_1 is in compression.

Lengths: ① $L_1 = \frac{70}{\sin 14} = 289 \text{ cm} = 2.89 \text{ m}$

② $L_2 = 2.48 \text{ m}$

③ $L_3 = 2.48 \text{ m}$

Member L1 is longest and has largest load of the three members. It is also in compression.

$$P_{cr} = 81863 \text{ N}$$

$$L = 2.89 \text{ m}$$

Assume ends are fixed-fixed $\Rightarrow C = 1$

$$\left(\frac{L}{K}\right)_1 = \sqrt{\frac{2\pi^2 E}{S_y}}$$

Assume Euler column

$$\frac{P_{cr}}{A} = \frac{C\pi^2 E}{(L/K)^2}$$

$$P_{cr} = \frac{C\pi^2 E I}{L^2} \quad I = \frac{\pi (d_o^4 - d_i^4)}{64} \text{ for hollow tube}$$

$$P_{cr} = \frac{C\pi^3 E (d_o^4 - d_i^4)}{64 L^2} \quad \text{assume } d_i = 0.9 d_o$$

$$d_o = \sqrt[4]{\frac{186.1 P_{cr} L^2}{C \pi^3 E}}$$

for boron-epoxy composite

$$E = 34.5 \times 10^6 \text{ psi} = 237.7 \text{ GPa} \quad (\text{along fiber axis})$$

$$E = 388 \times 10^6 \text{ psi} = 26.7 \text{ GPa} \quad (\text{against fiber axis})$$

$$d_o = 0.064 \text{ m} = 6.4 \text{ cm}$$

$$d_o = 2.52''$$

$$d_o = 0.111 \text{ m} = 11.1 \text{ cm}$$

$$d_o = 4.38''$$

for isotropic properties, a value of

$$E = 30 \times 10^6 \text{ psi} = 206.7 \times 10^9 \text{ Pa}$$

was found.

$$d_o = \sqrt[4]{\frac{(186.1)(81863)(2.89)^2}{(1)(\pi)^3(206.7 \times 10^9)}}$$

$$d_o = 0.067 \text{ m} = 6.7 \text{ cm}$$

$$\begin{aligned} d_o &= 2.64'' \\ d_i &= 2.37'' \end{aligned}$$

check tensile loads

assume force equally distributed over area

$$A = \frac{\pi(d_o^2 - d_i^2)}{4} = \frac{\pi(0.067^2 - 0.0603^2)}{4} = 6.7 \times 10^{-4} \text{ m}^2$$

$$\sigma = \frac{F}{A} = \frac{27463 \text{ N}}{6.7 \times 10^{-4} \text{ m}^2} = 41 \text{ MPa}$$

$$\sigma < \sigma_y \quad \sigma_y = 117 \text{ MPa}$$

Appendix 1E Joint Design

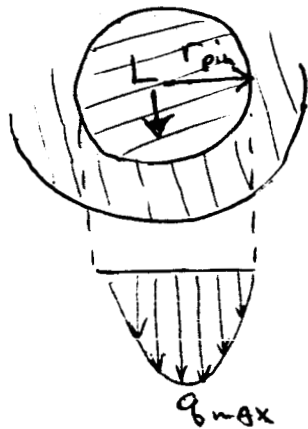
Joint Design Calculations

magnitude of body-femur joint load at worst case.

$$L = 142,400 \text{ N}$$

Based on a cosine load distribution, the maximum load/unit width in the joint is given by:

$$q_{\max} = \frac{2L}{\pi r_{\text{pin}}}$$



choosing an r_{pin} of 6 cm:

$$q_{\max} = \frac{2(142,400 \text{ N})}{\pi(0.06 \text{ m})} = 1.51 \times 10^6 \text{ N/m}$$

Using four TeflonTM cylinders of 30 cm. long (each), the maximum compressive pressure on the cylinder bearing surface is:

$$\begin{aligned} \sigma_{\max} &= \frac{q_{\max}}{2} = \frac{1.51 \times 10^6 \text{ N/m}}{1.20 \text{ m}} \\ &= 1.26 \times 10^6 \text{ N/m}^2 \end{aligned}$$

Assuming the desired velocity at the end of a leg to be 30.5 cm/s , the angular velocity at the joint is:

$$\omega = \frac{V_l}{\text{length}} = \frac{30.5 \text{ cm/s}}{425 \text{ cm}} = .0718 \frac{\text{rad}}{\text{s}}$$

Using this angular velocity, the sliding velocity at the interface between the joint pin and the bearing material is:

$$\begin{aligned} V_s &= r_{\text{pin}} \omega = .03 \text{ m} \left(.0718 \frac{\text{rad}}{\text{s}} \right) \\ &= 2.15 \times 10^{-3} \frac{\text{m}}{\text{s}} \end{aligned}$$

At this sliding velocity, the maximum pressure that can be applied to a PTFE + filler (i.e. bronze) bearing material is 10 MN/m^2 (Neale, Tribology Handbook, section A2)

And, the maximum static pressure for PTFE + fillers (i.e. bronze) ranges from $2-7 \text{ MN/m}^2$ (Neale, Tribology Handbook, section A2)

Thus, four 30 cm. long Tealon™ bearing cylinders with inside diameters of 6 cm. will satisfactorily carry orthopaed loads.

Appendix 2 Cost Analysis

Cost Analysis

Femur

| <u>Strut #</u> | <u>length (cm)</u> | <u># struts</u> | <u>total length (cm)</u> |
|----------------|--------------------|-----------------|--------------------------|
| 100 | 426.7 | 2 | 853.3 |
| 101 | 175 | 1 | 175 |
| 102 | 100 | 1 | 100 |
| 103 | 164 | 2 | 328 |
| 104 | 199.5 | 2 | 399 |
| 105 | 406.4 | 2 | 812.9 |
| 106 | 125.4 | 1 | 125.4 |
| 107 | 103.9 | 2 | 207.7 |
| 108 | 123.3 | 1 | 123.3 |
| 109 | 278.0 | 2 | 556 |
| 110 | 235.9 | 1 | 235.9 |
| 111 | 144.8 | 2 | 289.7 |
| 112 | 116.3 | 2 | 232.5 |
| | | | (4438.7) per leg |

Tibia

| <u>Strut #</u> | <u>length (cm)</u> | <u># struts</u> | <u>total length (cm)</u> |
|----------------|--------------------|-----------------|--------------------------|
| 200 | 100 | 1 | 100 |
| 201 | 57.9 | 1 | 57.9 |
| 202 | 425.7 | 2 | 851.4 |
| 203 | 82.1 | 2 | 164.2 |
| 204 | 72.2 | 2 | 144.4 |
| 205 | 106.3 | 1 | 106.3 |
| 206 | 71.0 | 2 | 142 |
| | | | (1566.2) per leg |

Body (175)(24) members = 4,200 cm

Total $3(4438.7 + 1566.2) + 4,200 = \boxed{22,214.7 \text{ cm}}$

find total volume of boron/epoxy
(approx. since center part of tube is honeycomb)

$$V = \pi (r_o^2 - r_i^2) L$$

$$= \pi (3.35^2 - 3.02^2) (22,214.7)$$

$$= 1.49 \times 10^5 \text{ cm}^3$$

$$124 \text{ cm}^3 \text{ cured boron/epoxy} \approx \$200$$

$$\therefore \text{cost of boron/epoxy} \approx \$240,500$$

Titanium

$$\text{Joints} \approx (6+6) 3 + 12 \approx 48 \times 1.32 \times 10^3 \text{ cm}^3 \approx 6.4 \times 10^4 \text{ cm}^3$$

$$\text{Rings} \approx 4(3) \approx 12 \times 302 \text{ cm}^3 \approx 3,624 \text{ cm}^3$$

$$\text{Feet} \approx 3(25,000) \approx 75,000 \text{ cm}^3$$

$$1 \text{ cm}^3 \approx 16\text{¢}$$

$$\therefore \text{cost of titanium} \approx \$22,800$$

Actuators

$$6 (\$1800) = \$10,800$$

Fuel Cells + Tanks

$$\$500,000$$

Total Material Cost - \$774,100

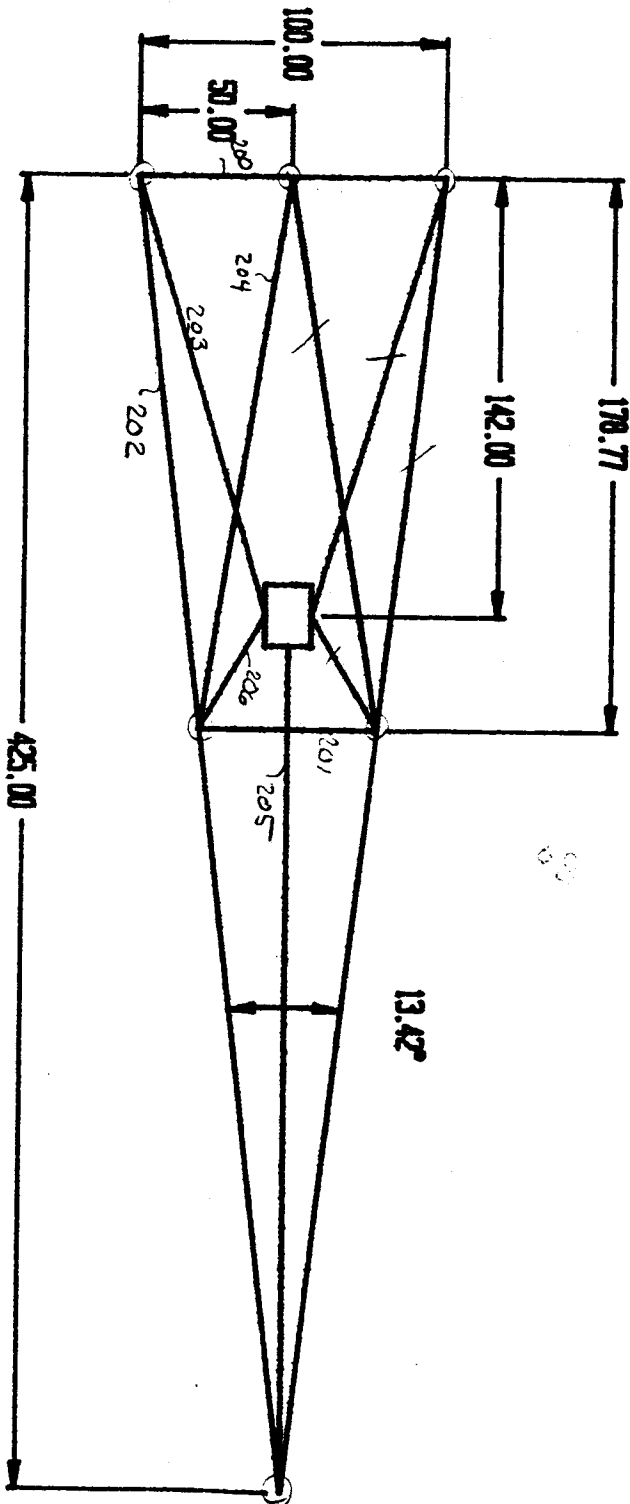
Shipping Costs

\$15,000 / lb

| <u>Item</u> | <u>Weight (lbs)</u> |
|--------------|---------------------|
| boron/epoxy | 663 |
| titanium | 1424 |
| actuators | 3678 |
| power supply | 4098 |
| <hr/> | |
| total | 9863 |

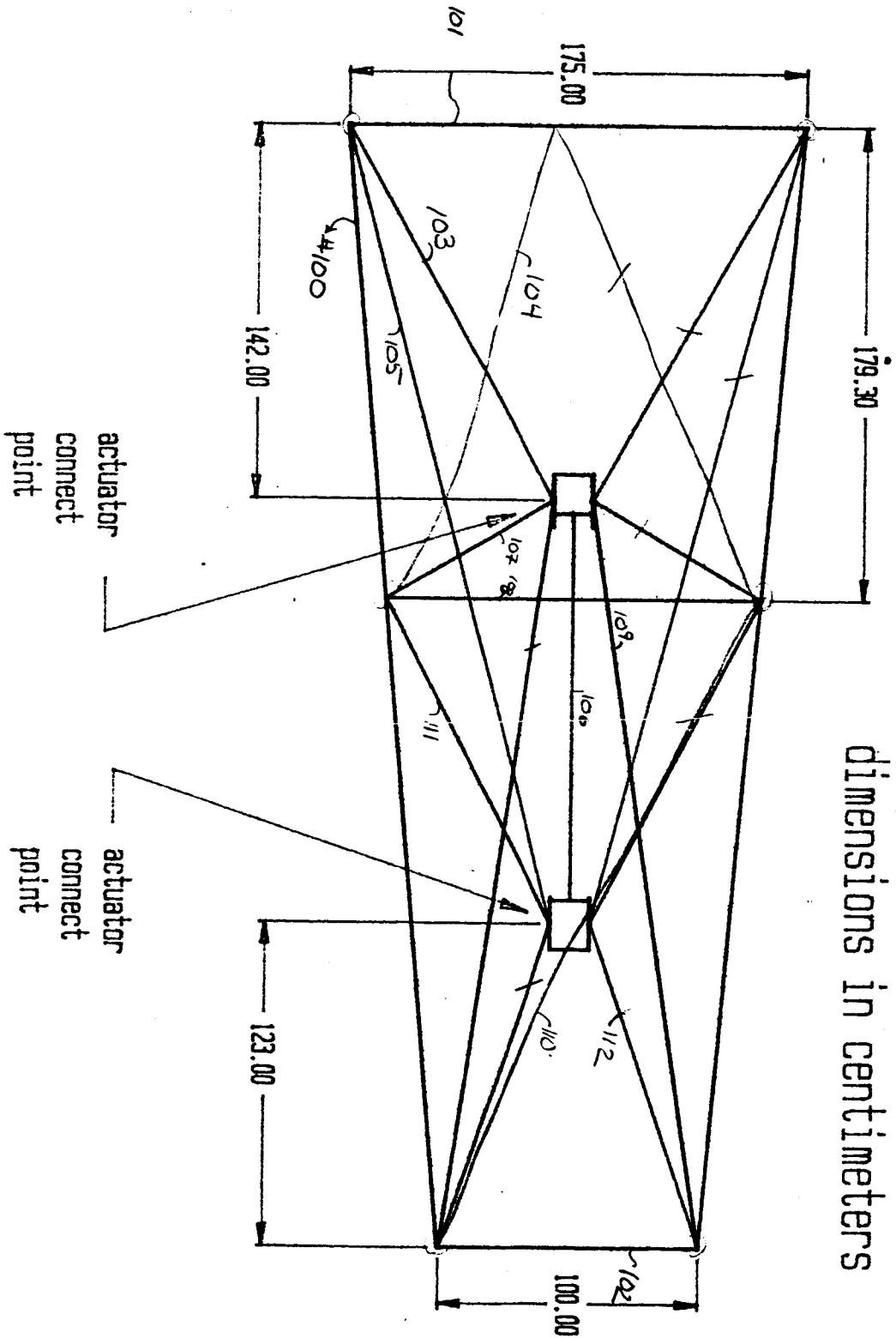
total shipping cost - \$148,000,000

Strut numbers
used in cost
analysis



Arthropod Tibia
(top view)
dimensions in centimeters

Strut numbers
used in cost
analysis

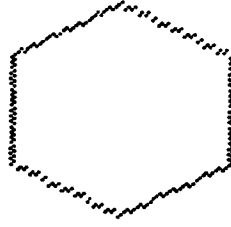


Appendix 3 Computer Program Outputs

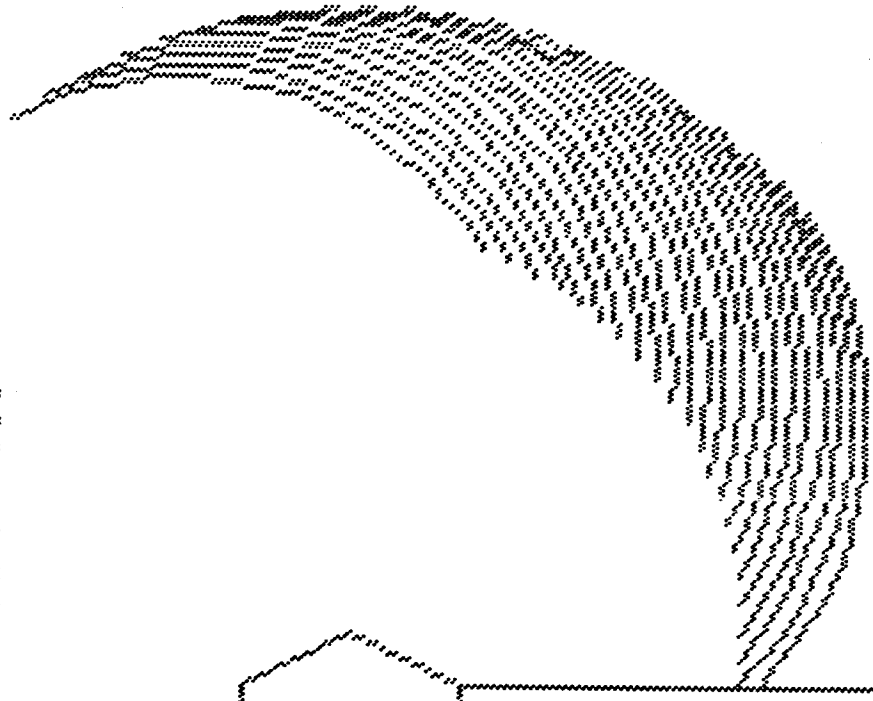
Appendix 3A Leg Sweep with Actuators

| | | | |
|-------|-------|------|----|
| Femur | (40%) | 3.31 | m. |
| Tibia | (60%) | 4.97 | m. |
| Total | | 8.29 | m. |

Skitter
height
above
ground :



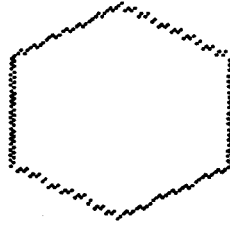
6.00 meters



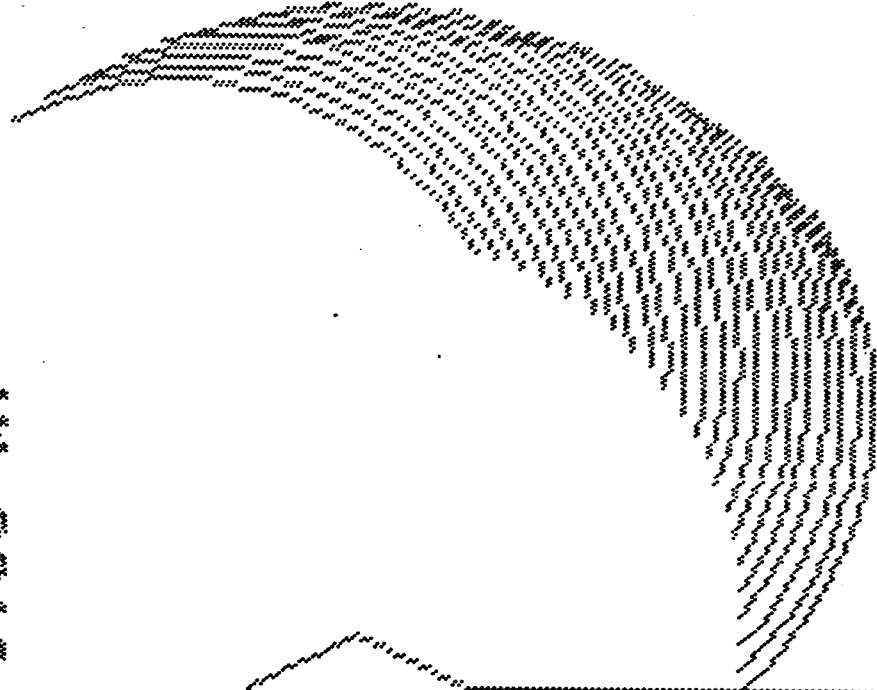
Plot of usable sweep area of leg.

| | | | |
|-------|-------|------|----|
| Femur | (42%) | 3.50 | m. |
| Tibia | (58%) | 4.83 | m. |
| Total | | 8.33 | m. |

Skitter
height
above
ground :



6.00 meters

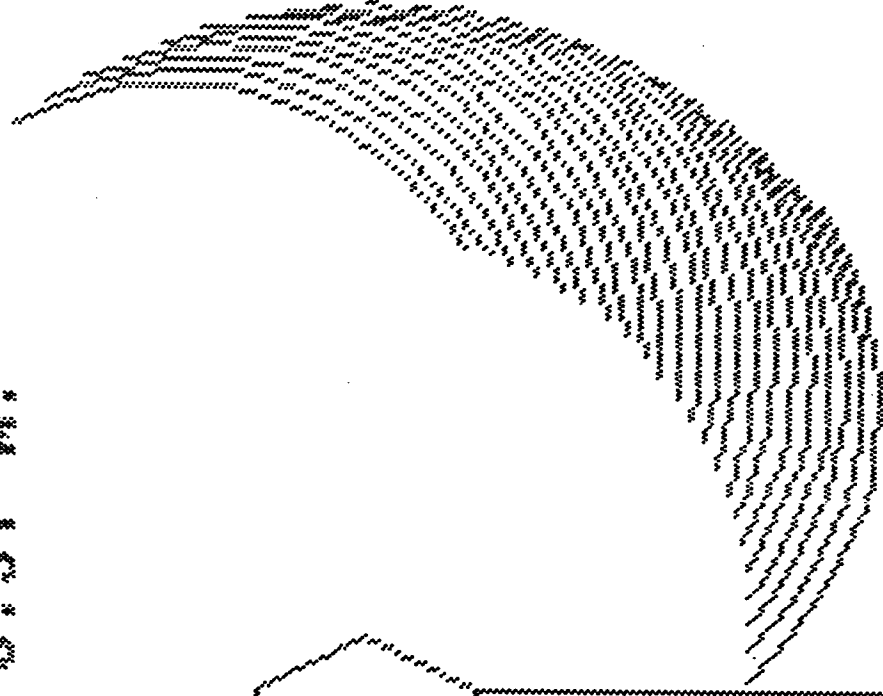


Plot of usable sweep area of leg.

| | | | |
|-------|-------|------|----|
| Femur | (44%) | 3.68 | m. |
| Tibia | (56%) | 4.69 | m. |
| Total | | 8.37 | m. |

Skitter
height
above
ground :

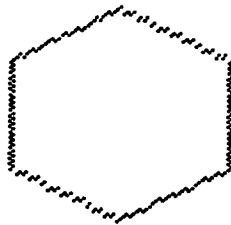
6.00 meters



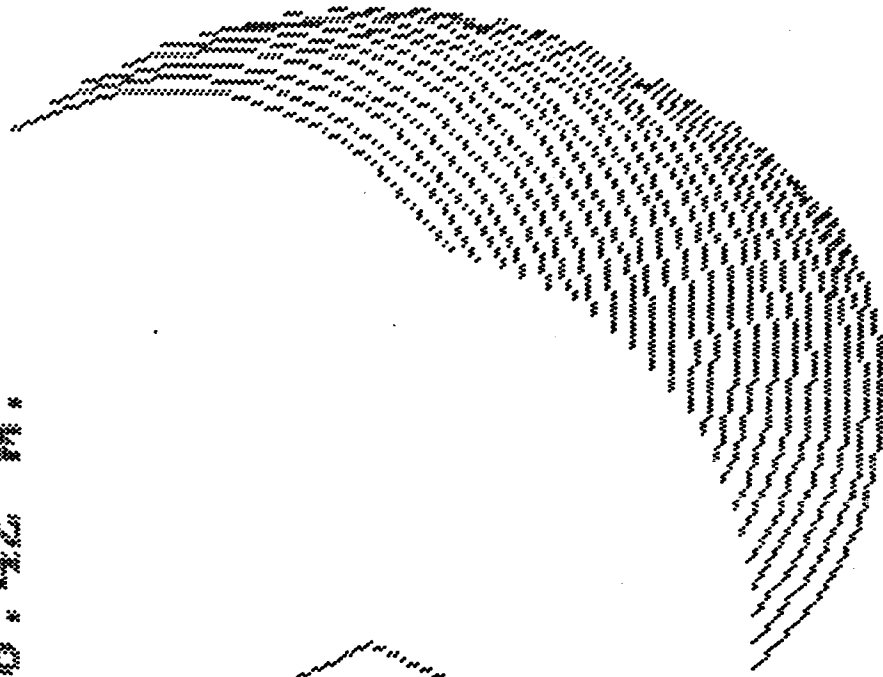
Plot of usable sweep area of leg.

| | | | |
|-------|-------|------|----|
| Femur | (46%) | 3.87 | m. |
| Tibia | (54%) | 4.54 | m. |
| Total | | 8.42 | m. |

Skitter
height
above
ground :



6.00 meters



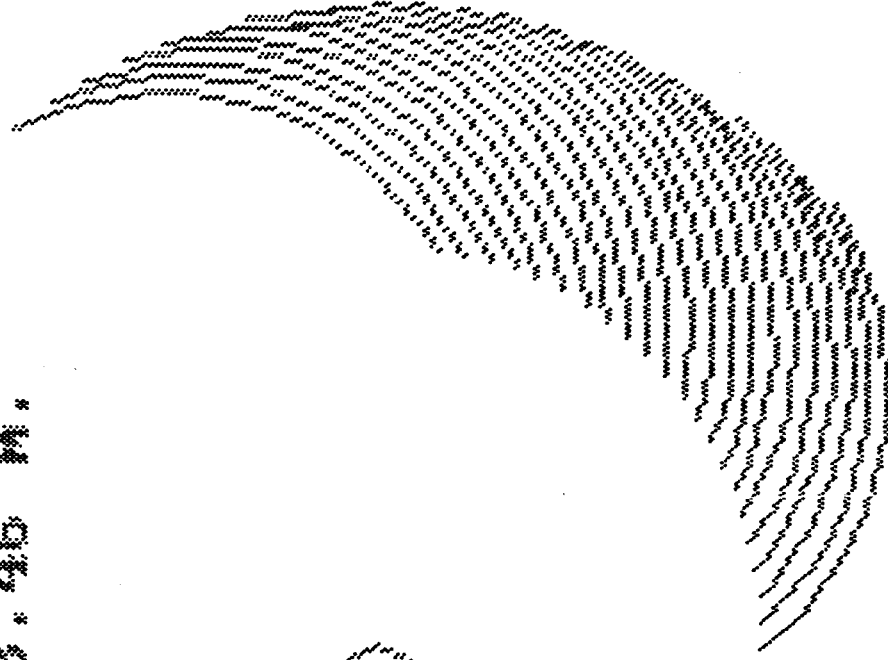
Plot of usable sweep area of leg.

| | | | |
|-------|-------|------|----|
| Femur | (48%) | 4.06 | m. |
| Tibia | (52%) | 4.40 | m. |
| Total | | 8.46 | m. |

Skitter
height
above
ground :



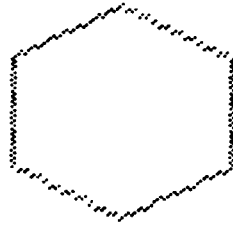
6.00 meters



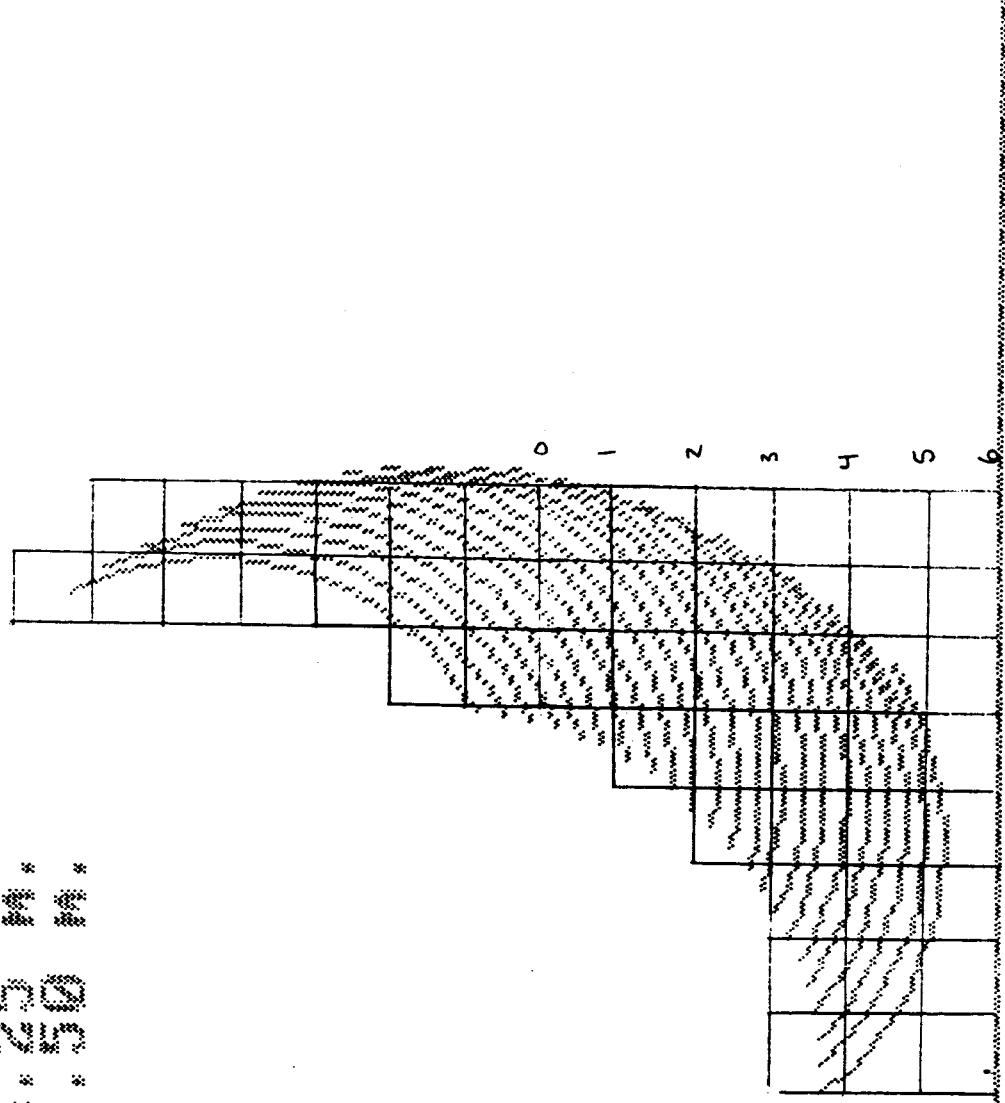
Plot of usable sweep area of leg.

Femur (30%) 4:25 m.
 Tibia (50%) 4:25 m.
 Total 8:50 m.

Skitter
 height
 around :



6.00 meters



Plot of usable sweep area of leg.

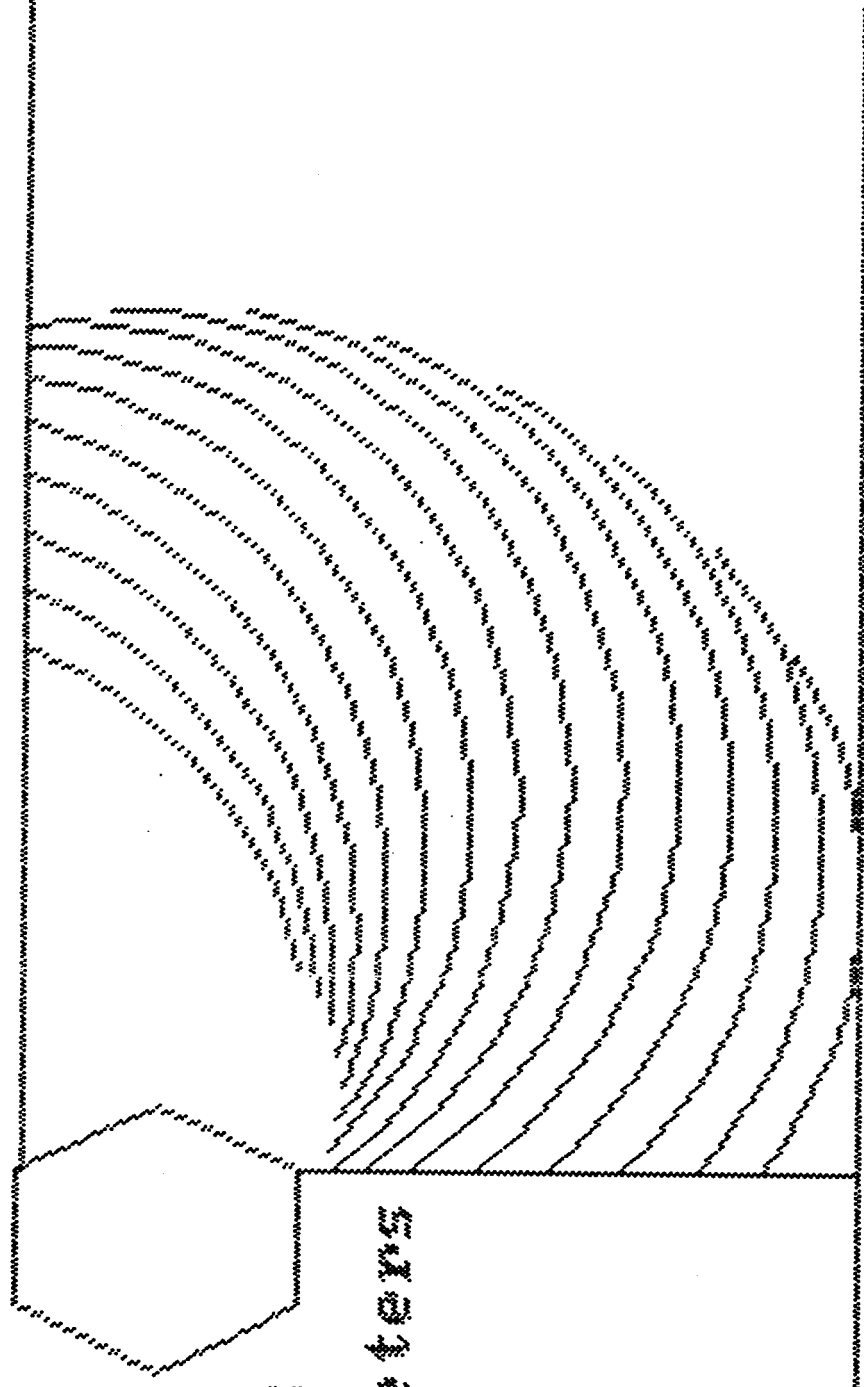
Appendix 3B Leg Sweep without Actuators

Plot of usable sweep area of leg.

| | |
|-------------|---------|
| Femur (40%) | 3.31 m. |
| Tibia (60%) | 4.97 m. |
| Total | 8.29 m. |

Skitter
height
above
ground :

6.00 meters

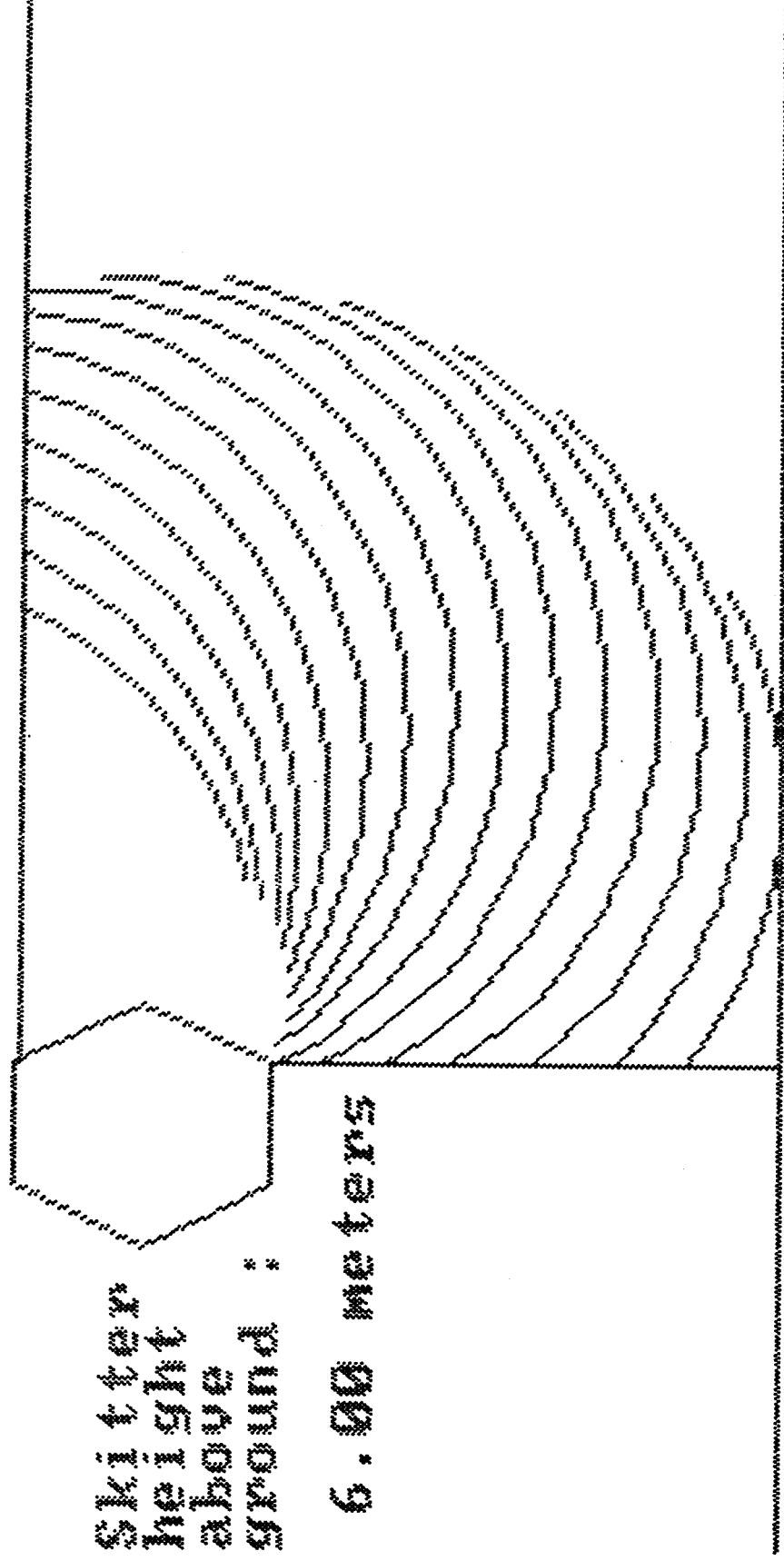


Plot of usable sweep area of leg.

| | |
|-------------|---------|
| Femur (42%) | 3.50 m. |
| Tibia (58%) | 4.83 m. |
| Total | 8.33 m. |

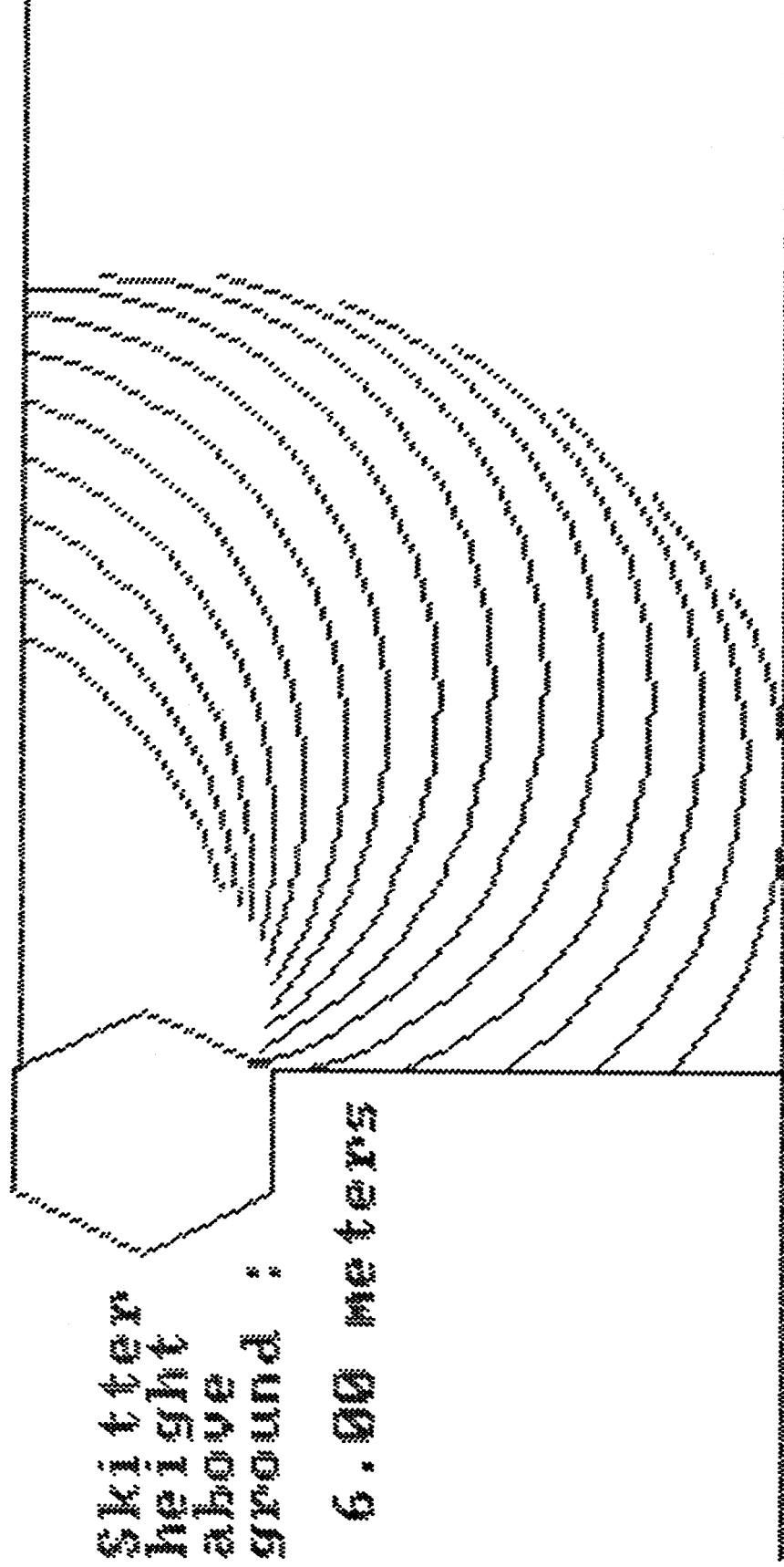
Skitter
height
above
ground :

6.00 meters



Plot of usable sweep area of leg.

Femur (44%) 3.68 m.
 Tibia (56%) 4.69 m.
 Total 8.37 m.

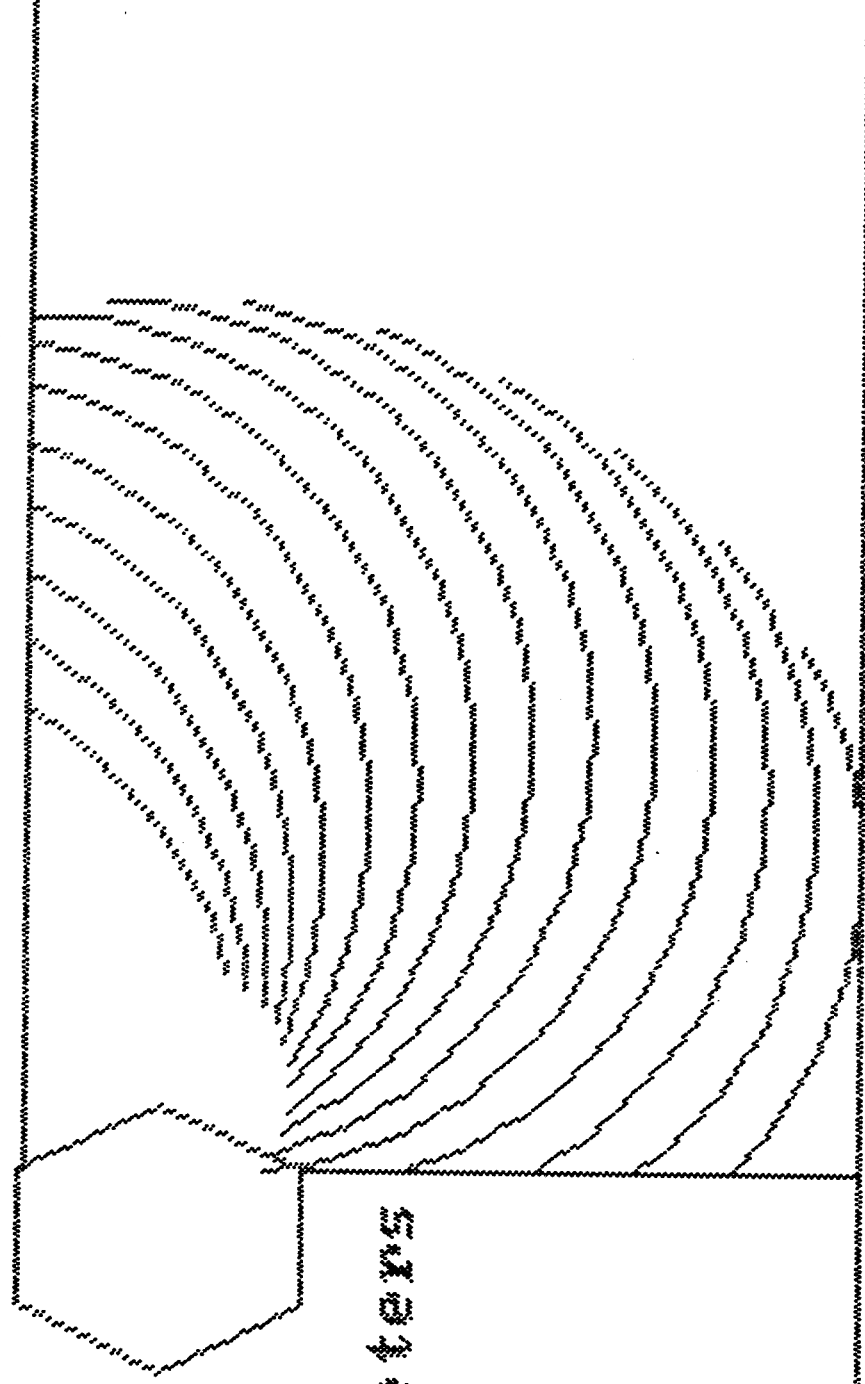


Plot of usable sweep area of leg.

| | |
|-------------|---------|
| Femur (45%) | 3.78 m. |
| Tibia (55%) | 4.62 m. |
| Total | 8.39 m. |

Skitter
height
above
ground :

6.00 meters

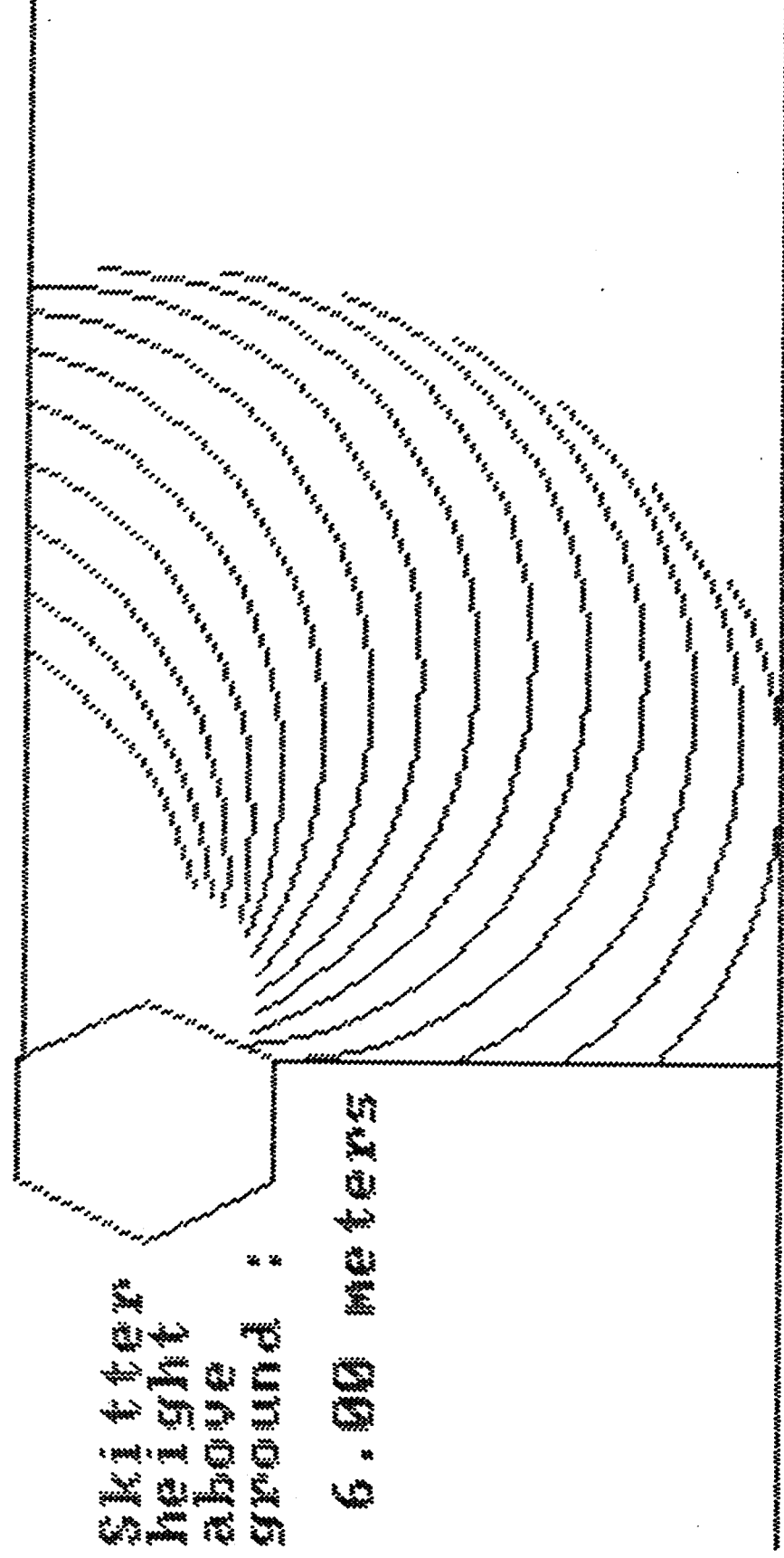


Plot of usable sweep area of leg.

| | |
|-------------|---------|
| Femur (46%) | 3.87 m. |
| Tibia (54%) | 4.54 m. |
| Total | 8.42 m. |

Skitter
height
above
ground :

6.90 meters

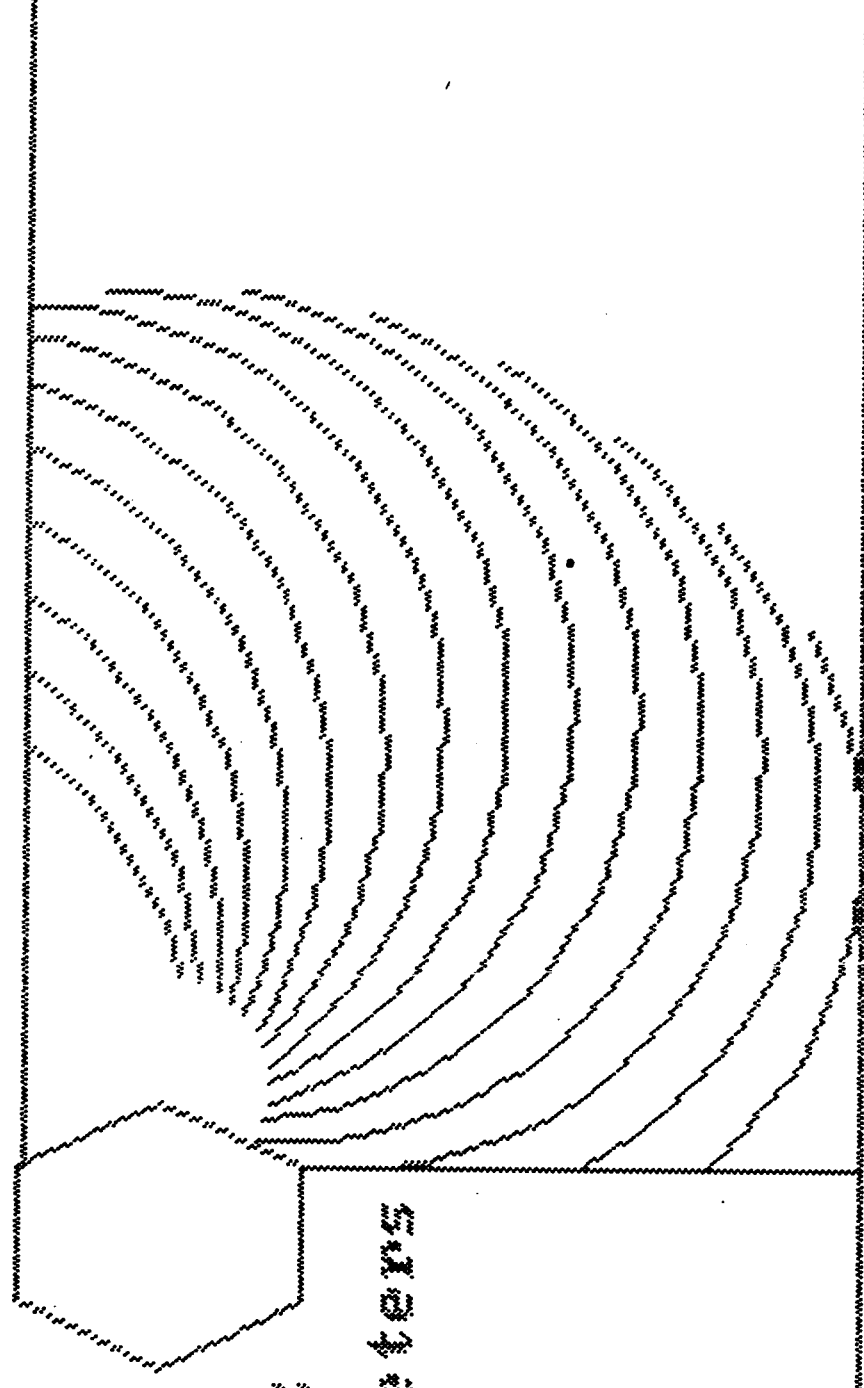


Plot of usable sweep area of leg.

Femur (48%) 4.06 m.
 Tibia (52%) 4.40 m.
 Total 8.46 m.

Skitter
 height
 above
 ground :

6.00 meters

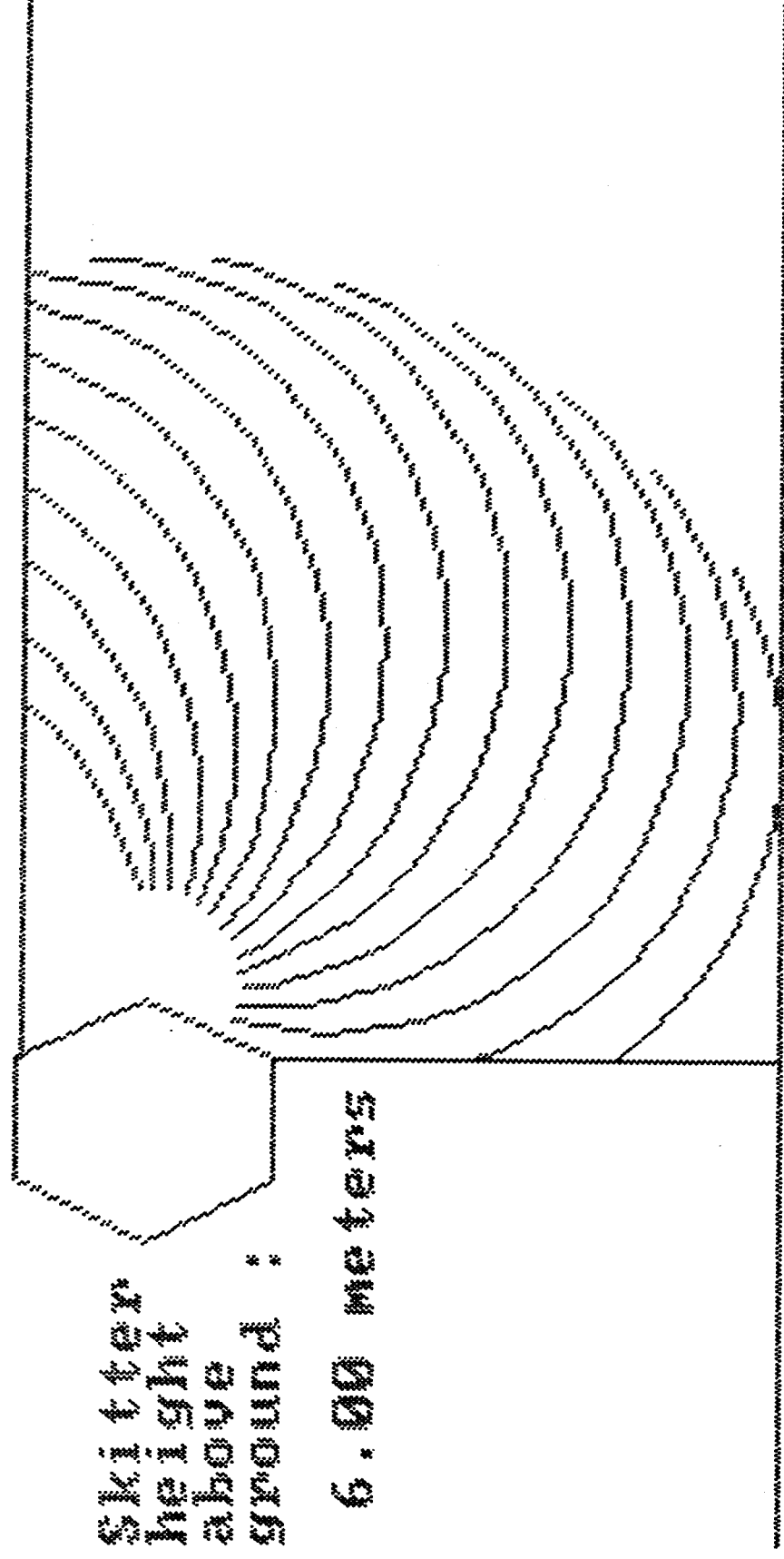


Plot of usable sweep area of leg.

| | |
|-------------|---------|
| Femur (50%) | 4.25 m. |
| Tibia (50%) | 4.25 m. |
| Total | 8.50 m. |

Skitter
height
above
ground :

6.00 meters



Appendix 3C Actuator Length Optimization

Skitter-femur Actuator optimization

| Full Length | Retract Angle | Extend Angle | Delta Angle |
|-------------|---------------|--------------|-------------|
| 0.10 | 1.97 | 3.28 | 1.31 |
| 0.20 | 3.94 | 6.56 | 2.63 |
| 0.30 | 5.90 | 9.85 | 3.94 |
| 0.40 | 7.87 | 13.14 | 5.27 |
| 0.50 | 9.85 | 16.45 | 6.60 |
| 0.60 | 11.82 | 19.77 | 7.95 |
| 0.70 | 13.80 | 23.11 | 9.30 |
| 0.80 | 15.79 | 26.46 | 10.68 |
| 0.90 | 17.78 | 29.84 | 12.07 |
| 1.00 | 19.77 | 33.25 | 13.48 |
| 1.10 | 21.77 | 36.69 | 14.92 |
| 1.20 | 23.78 | 40.16 | 16.38 |
| 1.30 | 25.79 | 43.67 | 17.88 |
| 1.40 | 27.81 | 47.23 | 19.41 |
| 1.50 | 29.84 | 50.83 | 20.99 |
| 1.60 | 31.88 | 54.49 | 22.60 |
| 1.70 | 33.93 | 58.21 | 24.27 |
| 1.80 | 36.00 | 61.99 | 26.00 |
| 1.90 | 38.07 | 65.86 | 27.79 |
| 2.00 | 40.16 | 69.81 | 29.65 |
| 2.10 | 42.26 | 73.86 | 31.60 |
| 2.20 | 44.38 | 78.02 | 33.64 |
| 2.30 | 46.51 | 82.30 | 35.79 |
| 2.40 | 48.66 | 86.73 | 38.07 |
| 2.50 | 50.83 | 91.33 | 40.50 |
| 2.60 | 53.02 | 96.13 | 43.11 |
| 2.70 | 55.23 | 101.16 | 45.93 |
| 2.80 | 57.46 | 106.47 | 49.01 |
| 2.90 | 59.71 | 112.14 | 52.43 |
| 3.00 | 61.99 | 118.26 | 56.26 |
| 3.10 | 64.30 | 124.98 | 60.68 |
| 3.20 | 66.64 | 132.57 | 65.92 |
| 3.30 | 69.01 | 141.52 | 72.51 |
| 3.40 | 71.42 | 153.19 | 81.78 |
| 3.44 | 72.39 | 159.61 | 87.22 |

Femur-tibia Actuator optimization

| Full Length | Retract Angle | Extend Angle | Delta Angle |
|-------------|---------------|--------------|-------------|
| 0.10 | 1.96 | 3.27 | 1.31 |
| 0.20 | 3.93 | 6.55 | 2.62 |
| 0.30 | 5.90 | 9.83 | 3.94 |
| 0.40 | 7.86 | 13.12 | 5.26 |
| 0.50 | 9.83 | 16.43 | 6.59 |
| 0.60 | 11.81 | 19.74 | 7.93 |
| 0.70 | 13.78 | 23.07 | 9.29 |
| 0.80 | 15.77 | 26.43 | 10.66 |
| 0.90 | 17.75 | 29.80 | 12.05 |
| 1.00 | 19.74 | 33.20 | 13.46 |
| 1.10 | 21.74 | 36.64 | 14.90 |
| 1.20 | 23.74 | 40.10 | 16.36 |
| 1.30 | 25.75 | 43.61 | 17.85 |
| 1.40 | 27.77 | 47.16 | 19.38 |
| 1.50 | 29.80 | 50.75 | 20.95 |
| 1.60 | 31.84 | 54.41 | 22.57 |
| 1.70 | 33.89 | 58.12 | 24.23 |
| 1.80 | 35.95 | 61.90 | 25.95 |
| 1.90 | 38.02 | 65.76 | 27.74 |
| 2.00 | 40.10 | 69.70 | 29.60 |
| 2.10 | 42.20 | 73.74 | 31.54 |
| 2.20 | 44.31 | 77.89 | 33.58 |
| 2.30 | 46.44 | 82.16 | 35.72 |
| 2.40 | 48.59 | 86.58 | 37.99 |
| 2.50 | 50.75 | 91.17 | 40.42 |
| 2.60 | 52.94 | 95.95 | 43.01 |
| 2.70 | 55.14 | 100.96 | 45.82 |
| 2.80 | 57.37 | 106.26 | 48.89 |
| 2.90 | 59.62 | 111.90 | 52.28 |
| 3.00 | 61.90 | 117.99 | 56.10 |
| 3.10 | 64.20 | 124.68 | 60.48 |
| 3.20 | 66.54 | 132.21 | 65.67 |
| 3.30 | 68.90 | 141.07 | 72.17 |
| 3.40 | 71.30 | 152.54 | 81.24 |
| 3.44 | 72.27 | 158.75 | 86.48 |

Appendix 4 Computer Programs

Appendix 4A Leg Length Optimization

```
program arthropod_leg;      {written in Turbo-Pascal V3.0 IBM PC version}
                           {written by Tony Smith, February 10, 1987}
```

```
{
REVISIONS
```

Version 2 of program added boundaries on leg movement.

Version 3 of program removed upper boundary of sweep.

Version 4 of program accounted for actuators restricting leg movement.

```
}
```

```
{$I graph.p}              {definitions for extended graphics}
```

```
const      hard_x = 87.5;   {x coordinate of hard point}
           hard_y = 751.0;  {y coordinate of hard point}
           max_y = 902;     {height of top of skitter}
           off_x = 100;     {x offset of picture}
           sin_50 = 0.76604; {sine of 50 degrees}
           alpha_inc = 0.069812; {2 degree increment}
           reduction = 8.8;  {reduction ratio of picture}
           ratio = 1.24;    {this gives proper perspective on printer}
                           {it is a multiplier for the x direction}
```

```
var  x_int,      {x-coord of end of leg in integer form}
     y_int,      {y-coord of end of leg in integer form}
     proportion : integer; {percentage that femur is of total length}

     alpha,      {angle femur makes with horizontal}
     beta,       {angle tibia makes with femur (negative)}
     tibia,      {length of tibia}
     femur       : real; {length of femur}
```

```
function radian (x:real):real;
begin
  radian := x * pi / 180.0;
end;
```

```
procedure formfeed;
```

```
begin
  writeln (1st, ^L)    {sends formfeed to printer}
end;
```

```
procedure printscreen;
```

```
type  regpack = record
           ax, bx, cx, dx, bp, si, di, ds, es, flags : integer;
        end;
```

```
var  recpack:      regpack;
```

```
begin
  intr($5,recpack);  {call printscreen interrupt}
end;

procedure initialize;

begin
  proportion := 40;    {set first proportion to plot}
end;

procedure find_leg_sizes (proportion : integer);

begin
  {to calculate leg sizes, it is assumed that the skitter is 6 meters
   high. The femur is all the way down (i.e. alpha = -50 degrees) and
   the tibia goes straight down to the ground.}
  tibia := 751.0 / ( 1 + proportion / ( 100 - proportion) * sin_50);
  femur := proportion * tibia / (100 - proportion);
end;

procedure reset_leg;

begin
  alpha := radian(47.61); {reset femur, tibia is reset in sweep_tibia}
end;

procedure sweep_tibia;

const  beta_inc = 0.08727;

var    old_x, old_y : integer;
       in_ground    : boolean;

begin
  {reset tibia to make -20 degree angle with femur axis.}
  beta := radian(-20.0);

  {reset in_ground flag, set true if leg tries to dig into the ground}
  in_ground := false;

  {calculate old values before entry into loop, will be same as first values}
  old_x := off_x +
    round(ratio *
      (hard_x+femur*cos(alpha)+tibia*cos(alpha+beta))/reduction);
  old_y := 179 -
    round((hard_y+femur*sin(alpha)+tibia*sin(alpha+beta))/reduction);

  {if either of these conditions is true the whole tibia sweep will be bad
   so exit}
```

```
if (old_y )= 179) or (old_x <= off_x) then exit;

repeat
  {calculate new points}
  x_int := off_x +
    round(ratio *
      (hard_x+femur*cos(alpha)+tibia*cos(alpha+beta))/reduction);
  y_int := 179 -
    round((hard_y+femur*sin(alpha)+tibia*sin(alpha+beta))/reduction);

  {if point is past vertical boundary, set x to boundary and interpolate y}
  if (x_int < off_x) then begin
    y_int := old_y + (y_int - old_y) * (off_x - old_x) div (x_int - old_x);
    x_int := off_x;
  end;

  {if point is below ground, set y to ground and interpolate x}
  if (y_int > 179) then begin
    in_ground := true; {this prevents stopping if leg just touches ground}
    x_int := old_x + (x_int - old_x) * (179 - old_y) div (y_int - old_y);
    y_int := 179;
  end;

  draw(old_x,old_y,x_int,y_int,1);

  {increment tibia and store last coordinates}
  beta := beta - beta_inc;
  old_x := x_int;
  old_y := y_int;

  {until tibia is swept or tibia goes under skitter or digs into the ground}
  until (beta (= radian(-107.6)) or (x_int = off_x) or in_ground;
end;

procedure increment_femur;

begin
  alpha := alpha - alpha_inc; {move femur to next position}
end;

procedure set_up_graphics;

var  x : integer;

begin
  {turn on graphics and clear the screen}
  graphmode;

  {plot in white}
  setpencolor(1);

  {put information on screen}
  writeln;
```

```

writeln;
writeln ('Femur (',proportion:2,'% ' ,femur/100:5:2,' m. ');
writeln ('Tibia (',100 - proportion:2,'% ' ,tibia/100:5:2,' m. ');
writeln ('Total      ',(femur + tibia)/100:5:2,' m. ');
writeln;
writeln;
writeln;
writeln ('Skitter');
writeln ('height');
writeln ('above');
writeln ('ground :');
writeln;
writeln;
writeln;
writeln ((hard_y - 151.0)/100:5:2,' meters');
writeln;
writeln;
writeln;
writeln;
writeln;
writeln;
writeln;
writeln ('Plot of usable sweep area of leg. ');

{draw the ground}
draw (0,179,319,179,1);

{draw vertical boundary of usable sweep area}
draw (off_x,round(179 - (hard_y - 151) / reduction),off_x,179,1);

{draw skitter, first set turtle at hard point}
setposition (round(-159 + off_x + hard_x / reduction),
            round(-79 + hard_y / reduction));

{point turtle in right direction}
setheading (330);

{and then draw each side of skitter}
for x := 1 to 6 do begin
    forwd(round(174.52 / reduction));
    turnleft(60);
end;
end;

begin {main program}
    initialize;
    repeat
        find_leg_sizes (proportion);
        reset_leg;
        set_up_graphics;
        repeat
            sweep_tibia;
            increment_femur
        until alpha (= radian(-39.61));      {end of sweep}
    until alpha (= radian(-39.61));
end;

```

```
    proportion := proportion + 2; {goto next proportion}
    printscreen;
    formfeed;
    until proportion = 52;
    textmode;
end.
```

Appendix 4B Upper and Lower Actuator Optimization

```
program actuator;

{
This program seeks to optimize the length for the skitter-femur actuator
of the skitter leg.

Optimum length is figured by which length affords the greatest arc swing.

The actuator is considered to be 60% of its extended length when compressed.
}

var  a,
      alpha_in,
      alpha_out : real;

function arccos (x : real) : real ;
begin
  if (x > -1.0) and (x < 1.0) then
    arccos := - arctan(x/sqrt(-x*x+1)) + pi/2  (good for -90 < x < 90 degrees)
  else begin
    clrscr;
    writeln (con,'ARCCOS OVERFLOW : ARGUMENT MUST BE  -1 ( X < 1. ');
    halt
  end;
end;

function degree (x : real) : real;
begin
  degree := x * 180.0 / pi
end;

begin {main program}
  a := 0.1;
  writeln (lst,'          Skitter-femur Actuator optimization');
  writeln (lst);
  writeln (lst);
  writeln (lst,'Full':18,'Retract':8,'Extend':8,'Delta':8);
  writeln (lst,'Length':18,'Angle':8,'Angle':8,'Angle':8);
  writeln (lst);
  repeat
    alpha_out := arccos ( (6.1082 - sqrt(a)) / 6.1082 );
    alpha_in := arccos ( (6.1082 - sqrt(0.6 * a)) / 6.1082 );
    writeln (lst, a:18:2 , degree(alpha_in):8:2, degree(alpha_out):8:2,
              degree (alpha_out - alpha_in):8:2);
    a := a + 0.1;
  until a > 3.4;
  a := 3.44;
  alpha_out := arccos ( (6.1082 - sqrt(a)) / 6.1082 );
  alpha_in := arccos ( (6.1082 - sqrt(0.6 * a)) / 6.1082 );
  writeln (lst, a:18:2 , degree(alpha_in):8:2, degree(alpha_out):8:2,
```

```
end.      degree (alpha_out - alpha_in):8:2);
```

```
program actuator2;
```

```
{
```

```
This program seeks to optimize the length for the femur-tibia actuator  
of the skitter leg.
```

```
Optimum length is figured by which length affords the greatest arc swing.
```

```
The actuator is considered to be 60% of its extended length when compressed.
```

```
}
```

```
var  a,  
      alpha_in,  
      alpha_out  : real;
```

```
function arccos (x : real) : real ;
```

```
begin
```

```
  if (x > -1.0) and (x < 1.0) then
```

```
    arccos := - arctan(x/sqrt(-x*x+1)) + pi/2 {good for -90 ( x < 90 degrees)}
```

```
  else begin
```

```
    clrscr;
```

```
    writeln (con,'ARCCOS OVERFLOW : ARGUMENT MUST BE -1 ( X < 1. ');
```

```
    halt
```

```
  end;
```

```
end;
```

```
function degree (x : real) : real;
```

```
begin
```

```
  degree := x * 180.0 / pi
```

```
end;
```

```
begin {main program}
```

```
  a := 0.1;
```

```
  writeln (1st, '          Femur-tibia Actuator optimization');
```

```
  writeln (1st);
```

```
  writeln (1st);
```

```
  writeln (1st, 'Full':18, 'Retract':8, 'Extend':8, 'Delta':8);
```

```
  writeln (1st, 'Length':18, 'Angle':8, 'Angle':8, 'Angle':8);
```

```
  writeln (1st);
```

```
  repeat
```

```
    alpha_out := arccos ( (6.125 - sqrt(a)) / 6.125 );
```

```
    alpha_in := arccos ( (6.125 - sqrt(0.6 * a)) / 6.125 );
```

```
    writeln (1st, a:18:2 , degree(alpha_in):8:2, degree(alpha_out):8:2,
```

```
              degree (alpha_out - alpha_in):8:2);
```

```
    a := a + 0.1;
```

```
  until a > 3.4;
```

```
  a := 3.44;
```

```
  alpha_out := arccos ( (6.125 - sqrt(a)) / 6.125 );
```

```
  alpha_in := arccos ( (6.125 - sqrt(0.6 * a)) / 6.125 );
```

```
  writeln (1st, a:18:2 , degree(alpha_in):8:2, degree(alpha_out):8:2,
```

```
degree (alpha_out - alpha_in):8:2);  
end.
```

Appendix 5 Material Properties and Equipment Specifications

Boron-Epoxy Composite Properties

Experiment vs Whitney-Riley Theoretical Model for Boron-Epoxy Composite

$$(E_f = 60 \times 10^6 \text{ psi}, \nu_f = 0.2, E_m = 0.6 \times 10^6 \text{ psi}, \nu_m = 0.35)$$

| Vol % fiber | E_1 (psi) <small>with grain</small> | | | E_2 (psi) <small>against grain</small> | | | G_{12} (psi) | | |
|----------------|---------------------------------------|--------------------|--------|--|--------------------|--------|--------------------|--------------------|--------|
| | Experiment | Theoretical | % Dif. | Experiment | Theoretical | % Dif. | Experiment | Theoretical | % Dif. |
| 20 | 11.7×10^6 | 12.5×10^6 | 6.84 | -- | -- | -- | -- | -- | -- |
| 55 | 30.1×10^6 | 33.3×10^6 | 7.80 | -- | -- | -- | -- | -- | -- |
| 60 | 35.7×10^6 | 36.2×10^6 | 1.40 | 3.10×10^6 | 3.08×10^6 | 0.65 | -- | -- | -- |
| 65 | 35.5×10^6 | 39.2×10^6 | 10.41 | 3.40×10^6 | 3.55×10^6 | 4.41 | -- | -- | -- |
| 70 | 34.5×10^6 | 42.2×10^6 | 23.30 | 3.88×10^6 | 4.20×10^6 | 8.25 | 1.77×10^6 | 1.09×10^6 | 38.4 |
| 75 | -- | -- | -- | 4.90×10^6 | 5.00×10^6 | 2.04 | 2.43×10^6 | 1.25×10^6 | 48.5 |

$$\text{Density} = 0.073 \text{ lb/in}^3 = 2021 \text{ kg/m}^3$$

$$\text{UTS} = 200 \times 10^3 \text{ psi} = 1379 \text{ MPa}$$

$$E = 30 \times 10^6 \text{ psi} = 206.7 \text{ GPa}$$

$$\text{Specific Stiffness} = 401 \times 10^6 \text{ in}$$

$$S_{\text{yield}} = 17 \text{ kpsi} = 117 \text{ MPa}$$

Titanium Alloy ASTM B265-58 T-5

$$\text{Specific gravity} = 4.54 \text{ g/cc}$$

$$E = 16 \times 10^6 \text{ psi} = 110.24 \text{ GPa}$$

$$\text{Coeff of linear expansion} = 8.5 \times 10^{-6} \text{ } ^\circ\text{C}^{-1}$$

$$S_y = 160 \text{ kpsi} = 1102.4 \text{ MPa}$$

$$S_{\text{ut}} = 170 \text{ kpsi} = 1171.3 \text{ MPa}$$

Actuator specifications

Model Number \Rightarrow Duff-Norton UM 9825-117
cost \Rightarrow \$2688.90 each

Dimensions

screw - dia - 3"
lead - 1"

gear box housing - 8.875" x 13.75" x 10.25"

actuator weight - 453 lbs

motor model number - T18R1301

motor cost - \$1800 each

motor weight - 160 lbs

Fuel Cells (will use 3)

Dimensions 14 x 17 x 40 inches

Weight 202 lbs

Reactant Storage

Four H₂ tanks

Dia - 45.5"

Capacity - 92 lbs/each

Four O₂ tanks

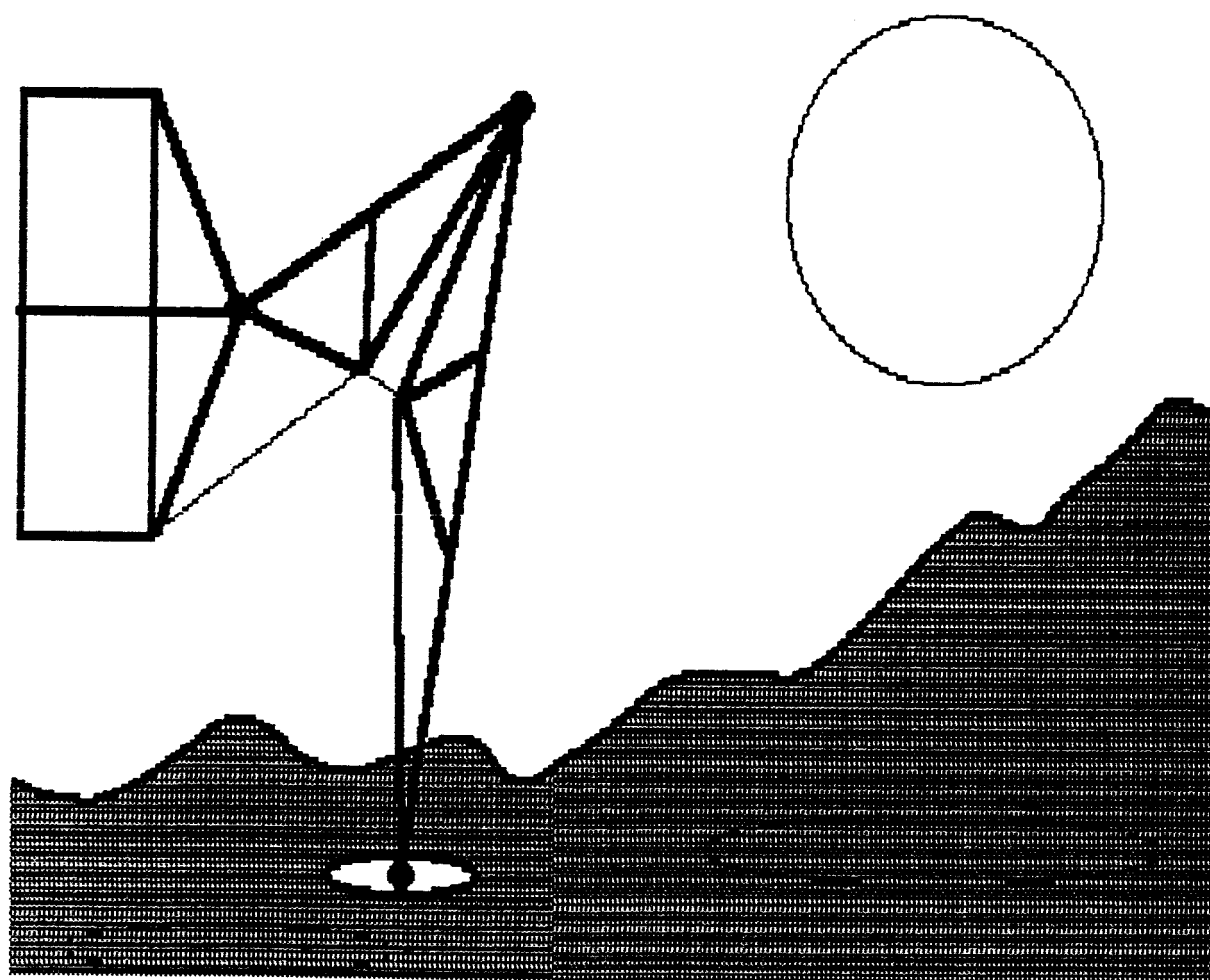
Dia. - 36.8"

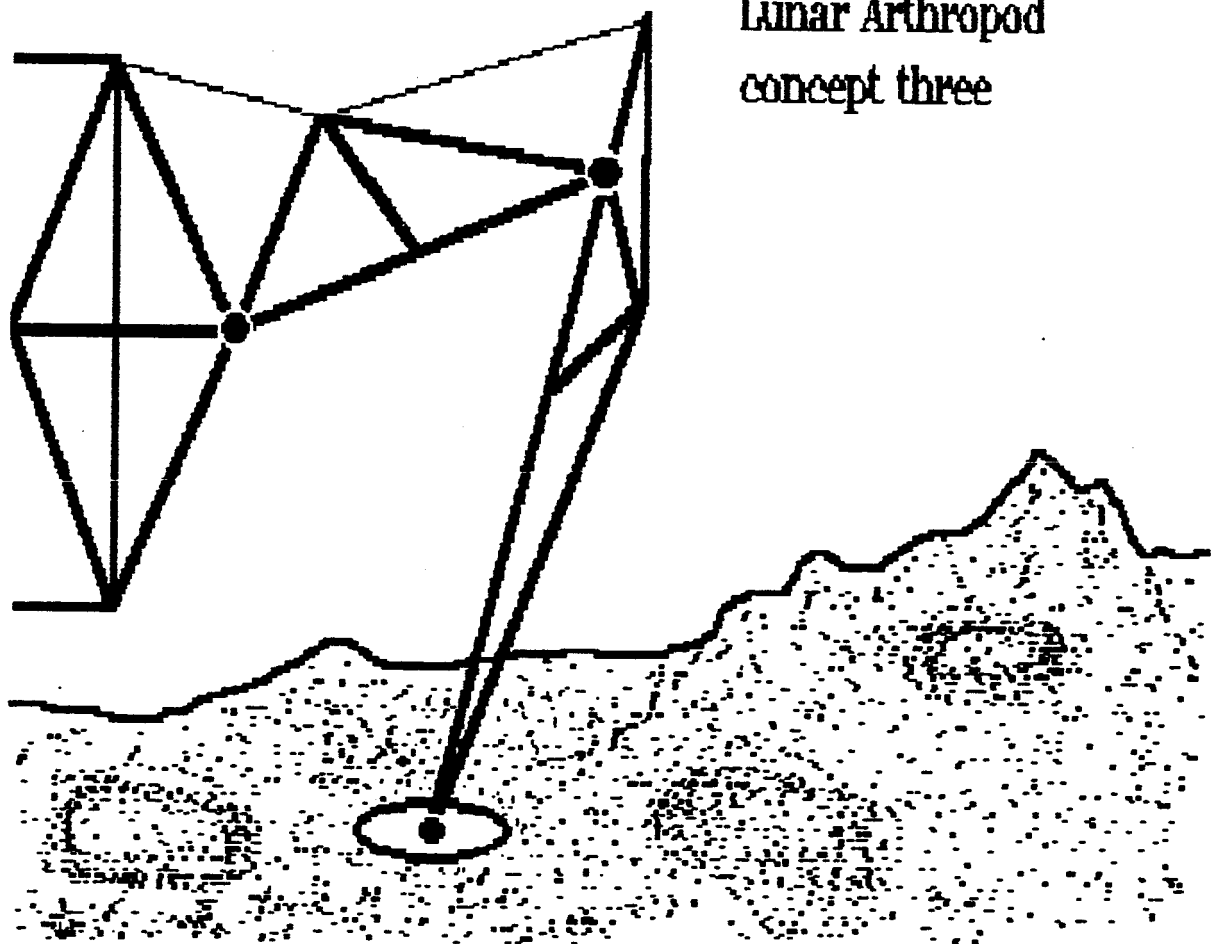
Capacity - 781 lbs/each

Total Weight of Power Supply - 4098 lbs

Cost - \$500,000

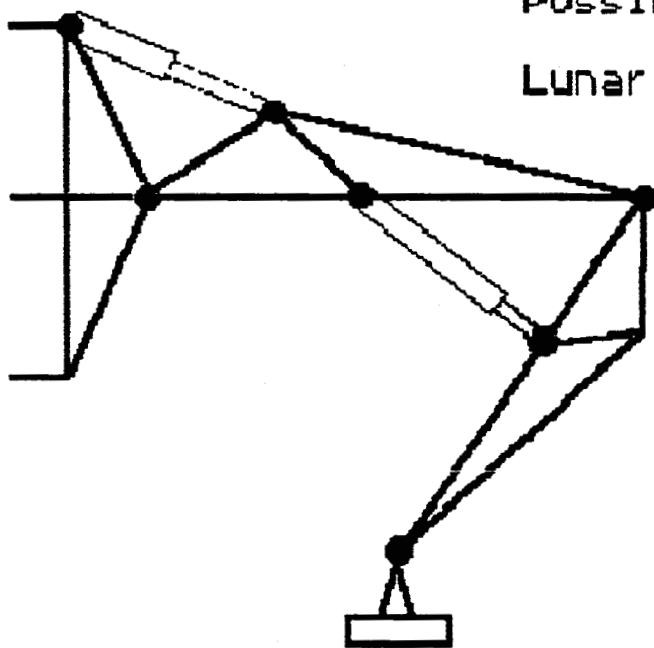
Appendix 6 Alternate Design Concepts



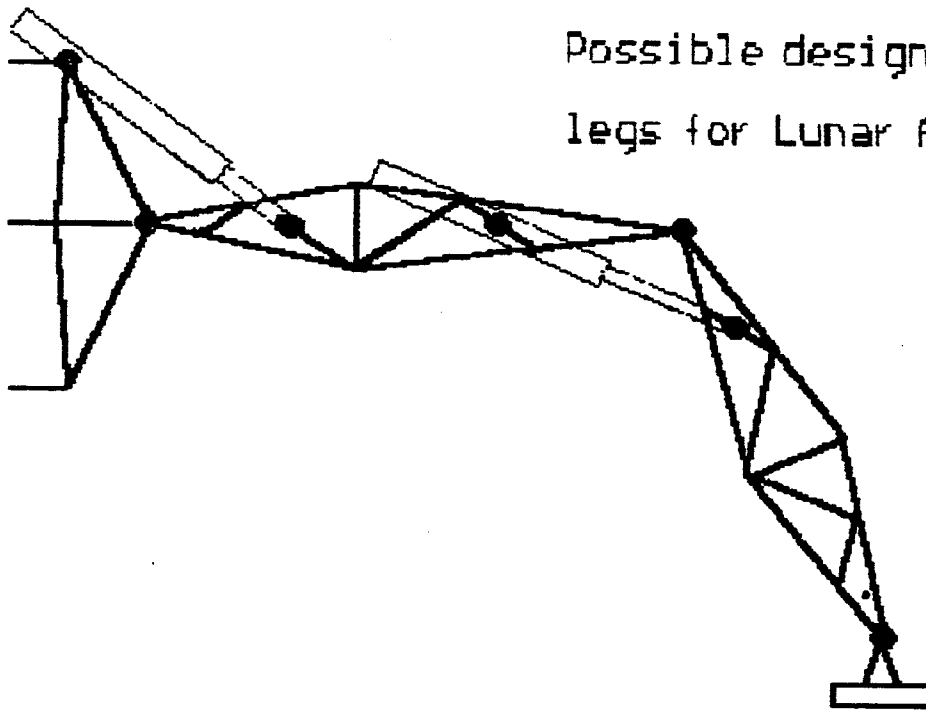


Lunar Arthropod
concept three

Possible design of
Lunar Arthropod legs



Possible design of
legs for Lunar Arthropod



Appendix 7 Progress Reports

January 14, 1987

MEMORANDUM

TO: Mr. Brazell
FROM: Group III (Arthropod Group)
SUBJECT: Weekly Progress Report

1. Eugene Fitcher, a professor at Oregon State University, was contacted about his research of insect legs. He stated that no real research has been done on the kinematics and dynamics of insect leg movements (his project has not really started). He did tell us that all insects have at least three members on their legs. Also, he said that no research has been done on robots with three legs, but that a lot has been done on four, six, and even one legged robots. Finally, he gave us some sources to check for robotic leg research (computer operated and multi-jointed). We are sending him a thank you note for spending time with us.

2. A program has been written to find the optimum dimensions of each leg segment. It does this by incrementing through all possible leg angles and checks if the points that are reached are usable. We have to decide on a few initial conditions (e.g. amount of angular displacement of upper leg) before this program will give us any data. As of now, it takes at least six hours on a PC to check one possible dimension.

3. Some sketches were made of possible leg configurations. Also, it was decided that we need to start off by finding out the needed performance characteristics of the skitter (e.g. maximum height, able to sit on the ground, parked position of legs, etc.)

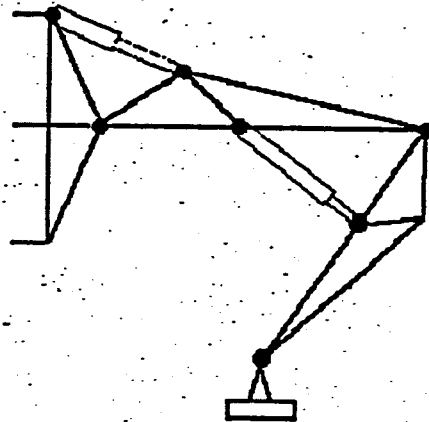
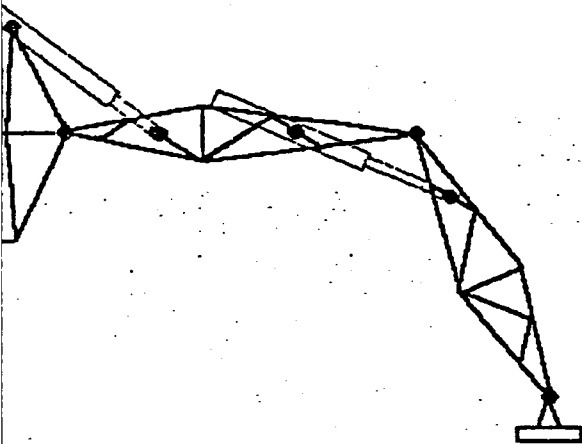
4. A preliminary draft of our problem statement has been written. It is listed below.

PROBLEM STATEMENT

The purpose of this project is to alter the existing leg design of a three-legged mobile platform intended to operate on the lunar surface. The design will incorporate a multi-jointed leg of the femur-tibia configuration. This project will seek to optimize this configuration by taking into account all pertinent parameters including but not limited to material, stresses, structure, and mobility.

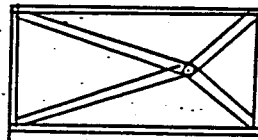
5. The entire group went to the Fernbank Science Center lecture on the lunar environment. After the lecture we watched the show. Both were interesting and informative.

Possible designs of
legs for Lunar Arthropod

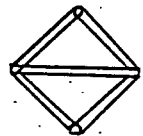


TOP LIMB

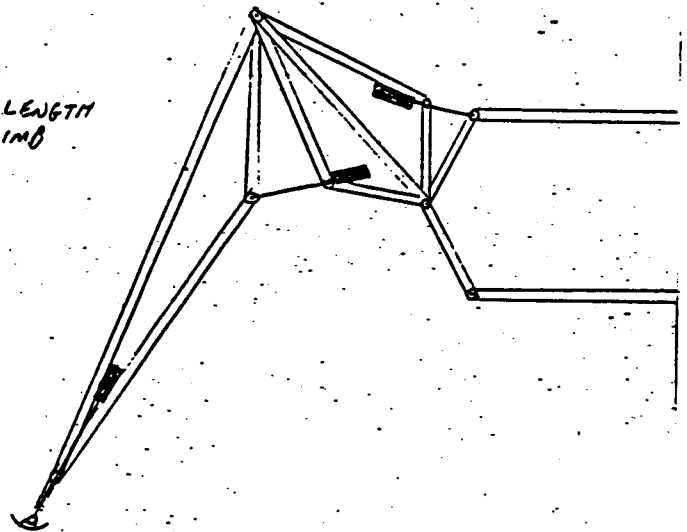
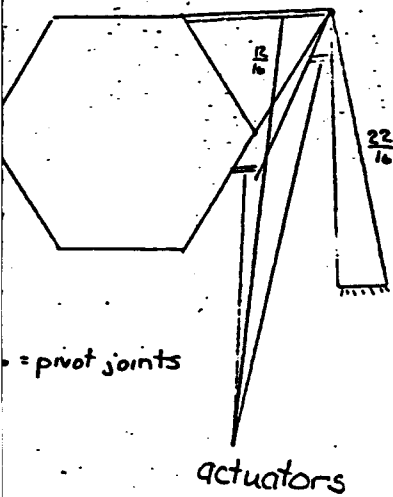
TOP VIEW



FRONT VIEW



BOTTOM LIMB LENGTH
TWICE TOP LIMB



BOTTOM LIMB

TOP VIEW



FRONT VIEW



January 21, 1987

MEMORANDUM

TO: Mr. Brazell
FROM: Group III (Arthropod Group)
SUBJECT: Weekly Progress Report

1. The program to optimize the leg segment sizes has been rewritten to perform the analysis graphically. This was done so as to obtain results in a shorter period of time. Also, some assumptions were arrived at (leg travel, max height, etc.) that were used in running the program. The optimum dimensions as far as reach only is concerned is 42% for the femur and 58% for the tibia. The range from 40% to 50% was very similar and really any of these dimensions could be used. This may happen if later it is found that another dimension serves another purpose better.

2. The group met and discussed areas that need to be researched and the direction our project should take. Subjects that will be researched include the lunar buggy and other space platforms, checking manufacturer's catalogs for different kinds of available joints and actuators, and lubrication.

3. We will be talking to Dr. Winer about solid lubrication. We believe that this may be an ideal way to lubricate the joints on the skitter due to no atmosphere.

4. We have spoken to Dr. J. G. Simitses about the use of composite materials. He told us what to look for and where to find it. In particular, he told us of a handbook of properties to look at that should be very helpful.

5. We have chosen a title for our project. It will be :

An Alternate Design for the Skitter Leg
A Femur-Tibia Approach

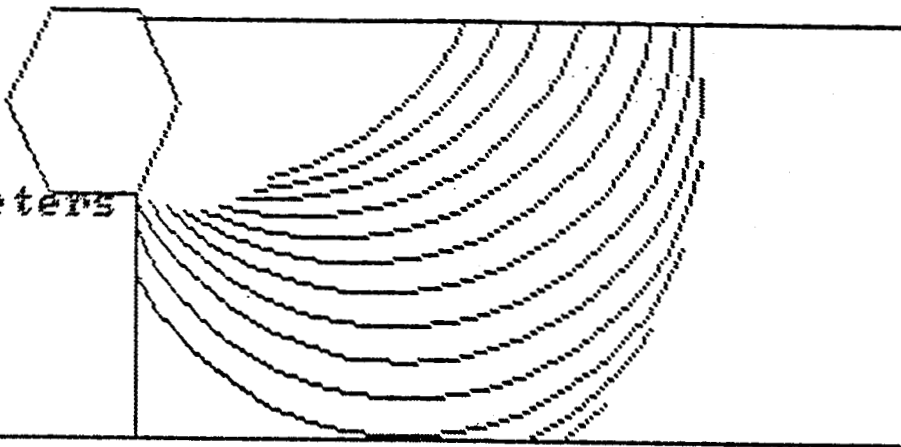
6. A second draft of our problem statement has been written.

Plot of usable sweep area of leg.

| | |
|-------------|---------|
| Femur (42%) | 3.50 m. |
| Tibia (58%) | 4.83 m. |
| Total | 8.33 m. |

Skitter
height
above
ground :

4.00 meters

A diagram showing a horizontal line representing the ground. A vertical line segment of 4.00 meters extends downwards from the ground line. To the left of this segment is a hexagonal shape. To the right, a series of curved lines represent the sweep area of the leg, starting from the 4.00 meter mark and extending to the right.

Plot of usable sweep area of leg.

| | |
|-------------|---------|
| Femur (42%) | 3.50 m. |
| Tibia (58%) | 4.83 m. |
| Total | 8.33 m. |

Skitter
height
above
ground :

6.00 meters

A diagram showing a horizontal line representing the ground. A vertical line segment of 6.00 meters extends downwards from the ground line. To the left of this segment is a hexagonal shape. To the right, a series of curved lines represent the sweep area of the leg, starting from the 6.00 meter mark and extending to the right.

January 28, 1987

MEMORANDUM

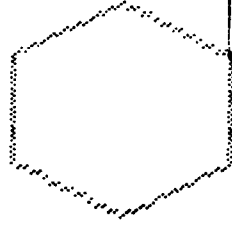
TO: Mr. Brazell
FROM: Group III (Arthropod Group)
SUBJECT: Weekly Progress Report

1. The final draft of our problem statement has been written.
2. The sweep area of the skitter leg for its entire range of motion has been plotted on a grid. We will be entering it into the drawing program on the HP computer. A lot of information can be gotten from this chart (e.g. max leg extension with skitter a certain distance above ground).
3. We talked to Dr. Simitzes again and he told us of three ASTM STP publications to look into. They cover testing and design of composites and composites for extreme environments.
4. We talked to Dr. Winer and he told us about three tribology references. They are the Tribology Handbook, Tribology Engineering, and Wear Control Handbook.
5. We have started to look into solid lubricants of the plastic variety.
6. We have a list of Aerospace Technical Reports that may be of interest to our group. However, the library only had a few of these. We are hoping to be able to get some from NASA.
7. We have started looking into different kinds of joints for the leg. We are starting our search with pin joints.

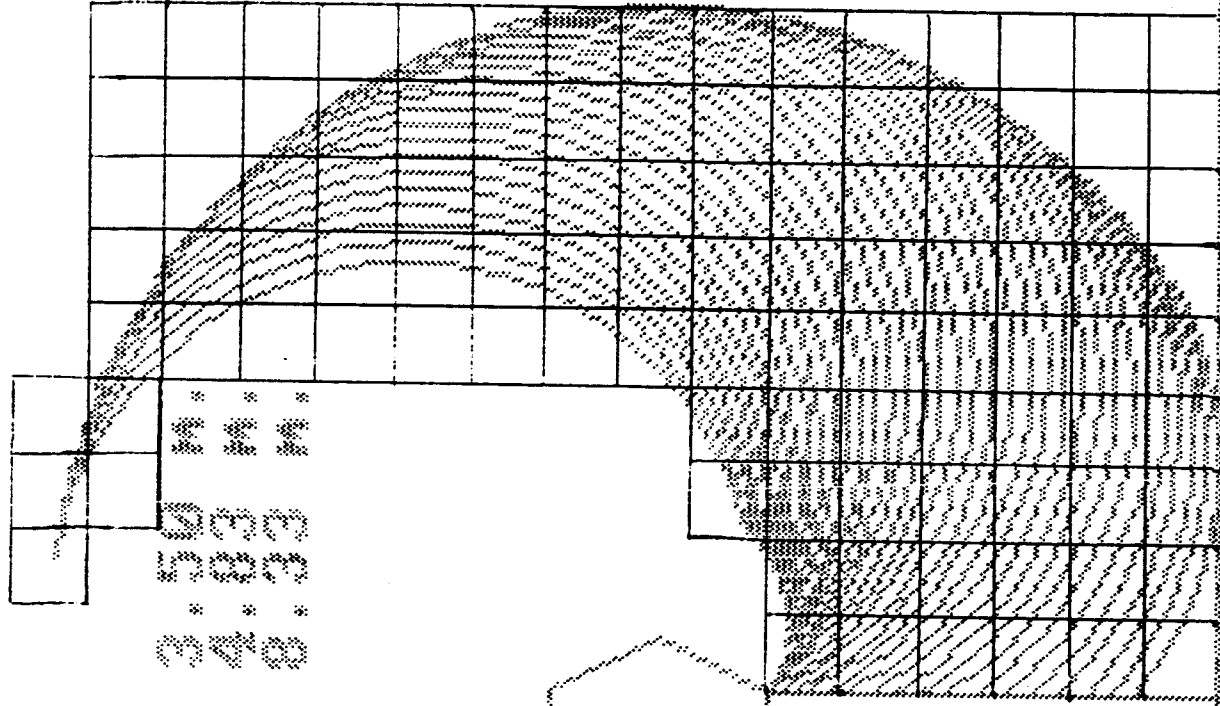
Femur (42%)
 Tibia (58%)
 Total

3:59 m.
 4:03 m.
 4:03 m.

Skitter
 height
 above
 ground :



6.00 meters



Plot of usable sweep area of leg.

February 3, 1987

MEMORANDUM

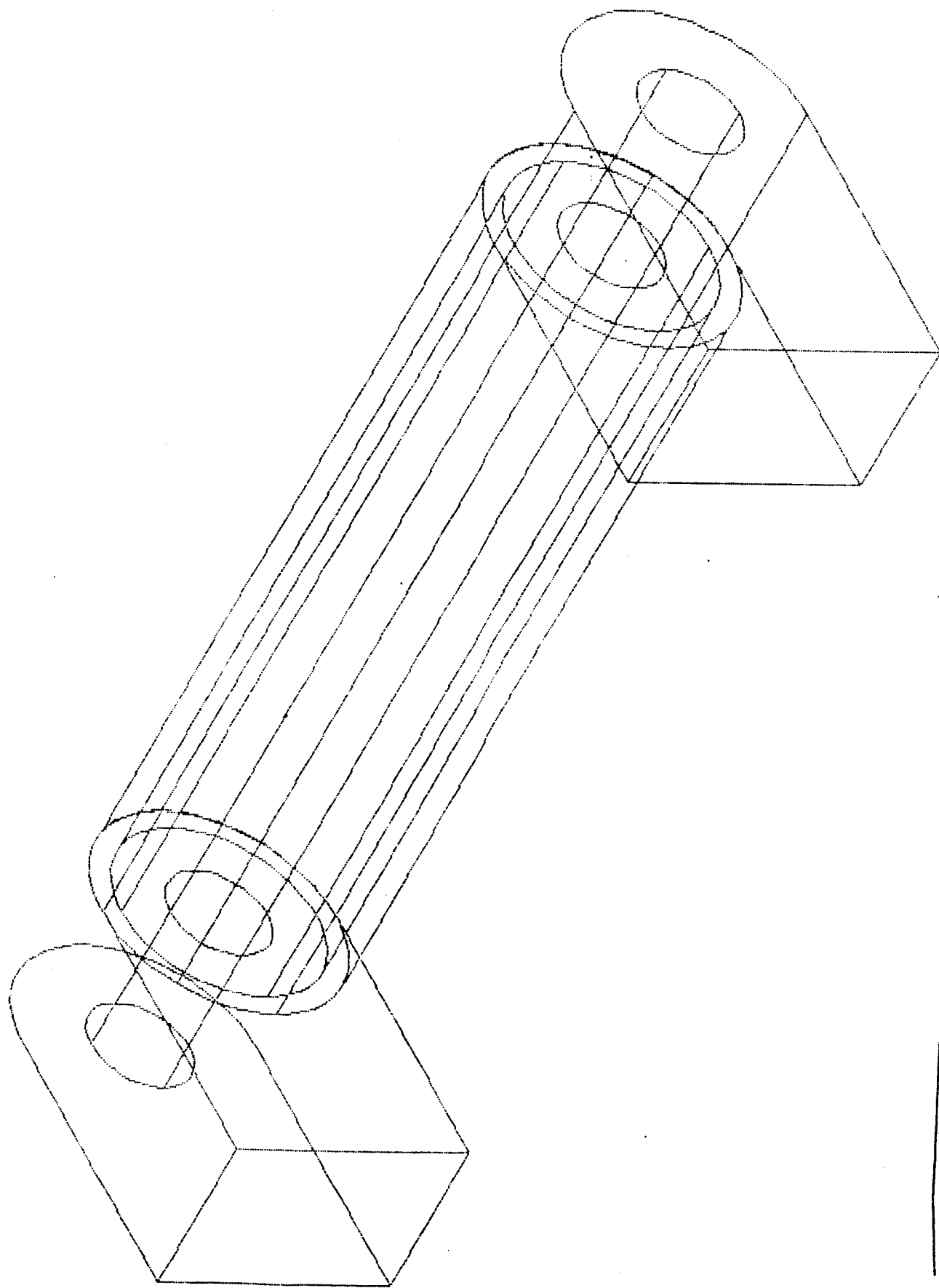
TO: Mr. Brazell

FROM: Group III (Arthropod Group)

SUBJECT: Weekly Progress Report

1. Our midterm presentation was prepared. Along with this, we have decided how we will progress with our project during the rest of the quarter.
2. We found a reference on Shuttle Materials. It seems like it will have a lot of valuable information regarding the selection of the material for the leg. Other references we have found include: Tribology Handbook, Test Methods and Design Allowables for Fibrous Composites, AE 4817 Class text, and another lubrication manual.
3. We have a conceptual design for the leg joints. A graphic is included with the report. It will be lubricated with a solid lubricant and will have some sort of 'dust' shield to protect the joints.
4. We have gathered information from references to help us start designing the leg. For example, the leg will be made of round tubing vs. square tubing. NASA studies have shown that a 30-40% weight savings is obtained using round tubing. Also, this will be a better shape for the use of composites. We plan to use a woven composite so as to approach isotropic material properties.

Arthropod leg joint



February 10, 1987

MEMORANDUM

TO: Mr. Brazell

FROM: Group III (Arthropod Group)

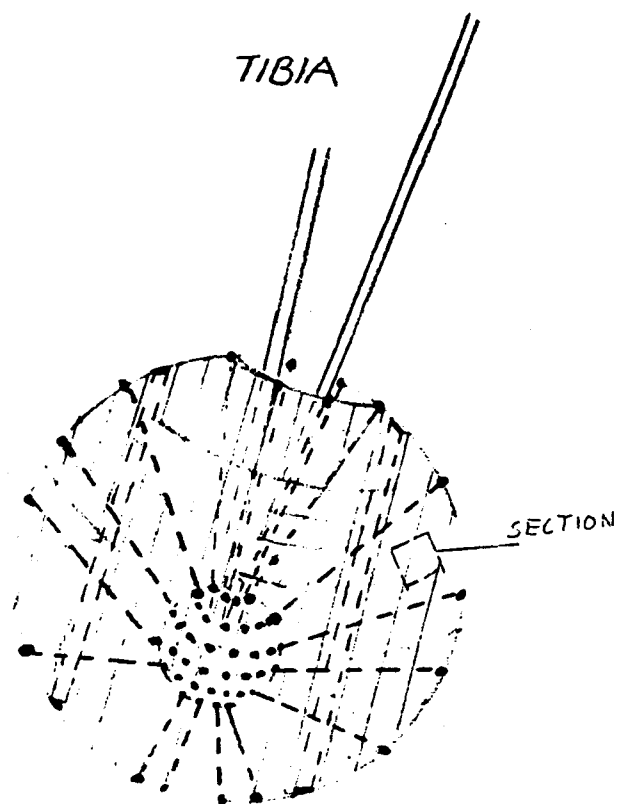
SUBJECT: Weekly Progress Report

1. We have narrowed our materials choice down to two materials, with the leader being a boron epoxy composite. We are currently trying to get more low temperature data on the material. We are trying any manufacturers, etc.

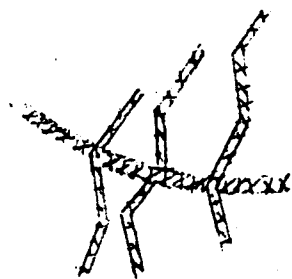
2. The sweep area of the leg has been recalculated taking into account the effect of actuator motion. Since the actuators will limit the angular sweep of each segment of the leg, the area is now much smaller. However, it still appears to serve all of the intended purposes (i.e. a 4m stroke for the drill, and a fairly good reach to stabilize the crane).

3. We are beginning to design a foot for the leg. Now that there is no actuator at the bottom of the leg, a foot will be very desirable. Some of the ideas presented so far is that it should be of minimum weight, very durable and most likely not pivoted. So that it will work at any leg angle, it will be somewhat hemispherical.

4. We are continuing our design of the joints. We believe that pin joints are a viable alternative. With a combination of a boot and a labyrinth seal, we believe that the joint could be very effectively sealed from the environment. This is more of an alternative to us than the digger group because our joints will not be dragged through the soil.



Suspension Configuration For Foot



MESH.

February 18, 1987

MEMORANDUM

TO: Mr. Brazell

FROM: Group III (Arthropod Group)

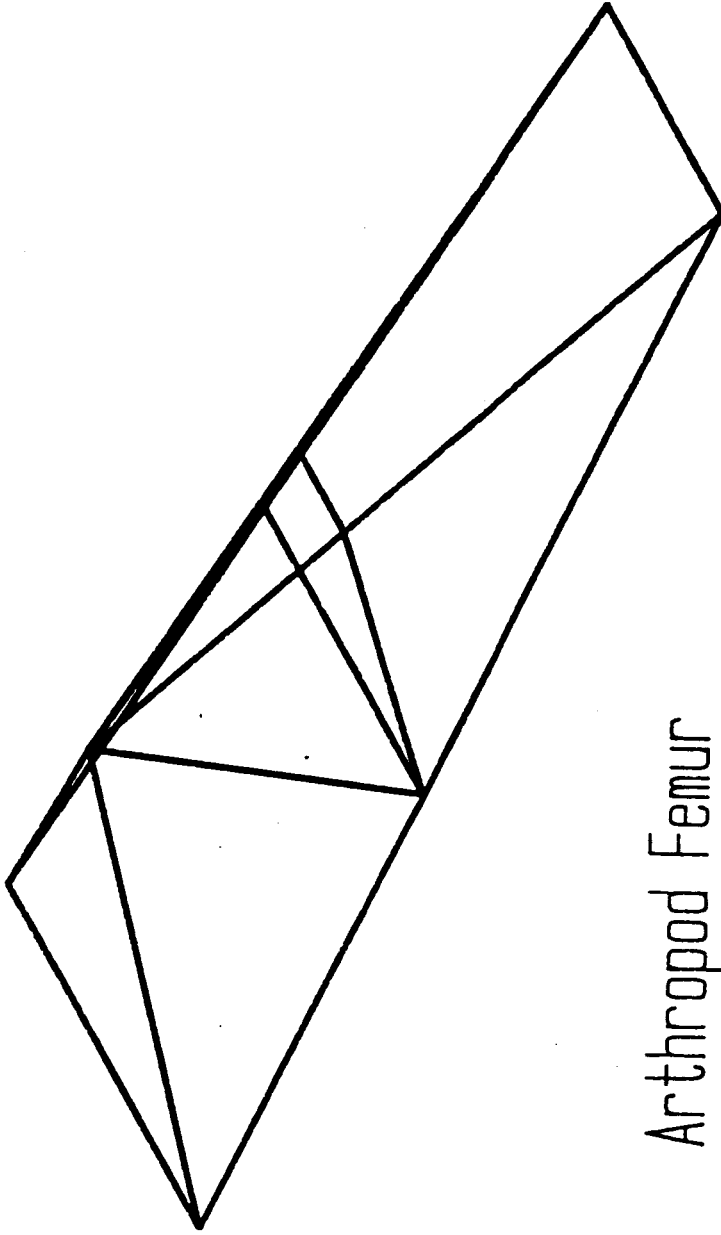
SUBJECT: Weekly Progress Report

1. We spoke with a representative at NASA who strongly advised us against using hydraulic actuators. He is sending us information on rotary ball screw and jack actuators which he said is the current 'best' alternative. He is also sending us all the available information he can find on the boron epoxy composite we are considering.

2. We are checking for manufacturers of the boron epoxy composite. We need to contact them to find out the low temperature properties of the composite. So far, we have only found the properties from 200F to -150F. We still need to find out about the lower 50F.

3. We have performed force analyses on the leg for the crane load. We believe that the crane will be the most limiting component the skitter uses. It appears that buckling of the leg at full crane load will be a design constraint. We are checking on how to perform the buckling analysis since the leg will have multiple members.

4. We are still working on the foot design of the leg. It appears that the hemispherical foot made of metal straps will work out the best since it will have no moving parts. It will be attached at the bottom to the leg and be cross-braced at the top to the members.



Arthropod Femur

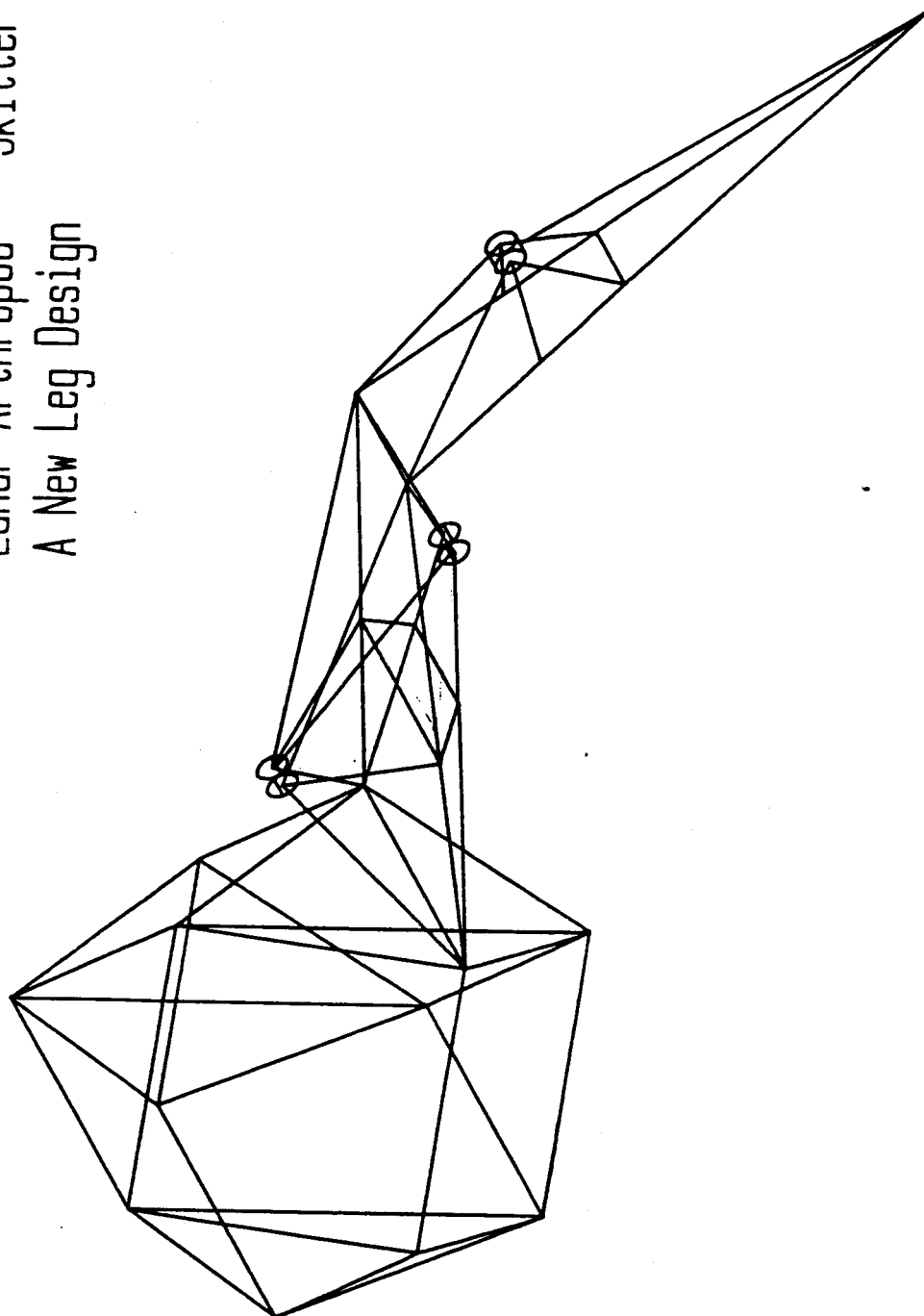
February 25, 1987

MEMORANDUM

TO: Mr. Brazell
FROM: Group III (Arthropod Group)
SUBJECT: Weekly Progress Report

1. We have made a structural design for the leg. There should be only a few minor changes to do.
2. We are calling around to obtain more data on ball screw actuators.
3. We have researched the references that NASA gave us the names of. One is not in the library and we are checking to see if it is available elsewhere. The other was checked out and we have placed it on hold.
4. We are still progressing on the foot design. One reference we are looking at is the NASA report on the lunar buggy. It has some very good data on lunar soil.
5. We have made assignments to the team members on writing the report. A preliminary first draft should be ready in a little over a week. We will be writing an outline shortly.

Lunar Arthropod - 'Skitter'
A New Leg Design



March 3, 1987

MEMORANDUM

TO: Mr. Brazell

FROM: Group III (Arthropod Group)

SUBJECT: Weekly Progress Report

1. We have organized a schedule that outlines our activities up to the time of the presentation. The things left to do are concerned mainly with the preparation of the written and oral presentation.
2. We have made an outline for our paper and have made writing assignments to the different team members. The paper will be prepared and reviewed this coming weekend.
3. We are analyzing the forces in the individual members at the time of worst case loading on the leg. Due to lack of time to become proficient in a computer program to perform truss force analysis, we are doing this manually.
4. We will be building a model the night of March 4. The materials have been purchased.

Arthropod Femur
(side view)
dimensions in centimeters

